A System Dynamics Model for the Strategic Analysis of Options for Sourcing Engineering Design

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Submitted to the Sloan School of Management & the Engineering Systems Division in the MIT School of Engineering

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ABSTRACT

EC (Engineering Change) is the natural by-product of the Engineering Design process. There are two types of EC: Revisions and Defects Correction. Revisions arise because Engineering Design is an iterative process, requiring Engineers to implement necessary Revisions to the design of a product or systems to improve performance measures. Defects on the other hand are pure design errors, and arise from the fact that the Engineering Design work is not being accomplished with Perfect Quality. These Defects must therefore be corrected in what is termed Rework.

EC is the critical factor in determining Lead Time and Labor cost of an Engineering Design work. The generation of Rework – requiring EC depends on several factors including : Quality, Design Complexity, Time to Discover Rework, Time for Issues Resolution, Hiring New and less experienced staff and Over Time work. This thesis presents a Systems Dynamics Model which incorporates these factors as exogenous variables to enable the simulation of their impacts on endogenous variables such as Lead Time and Labor costs. Since these factors exhibit wide variability when the Engineering Design is accomplished In-House compared to when it is Outsourced, the model is therefore a tool that can help an OEM in the Strategic Analysis of Options for the Sourcing of Engineering Design work.

A simulation example is given in which an Engineering Design with 474 Initial Designs required 400 fully experienced Engineers to accomplish in 360 Days and a quality level of 52% (the Baseline case). The OEM had only 200 fully experienced Engineers on hand. Facing a staff capacity constraint, this OEM therefore explores a number of In-House Sourcing Options (Hiring and Over Time) and a number of Outsourcing Options (Suppliers with staff capacities of 400 to 1,000, and low (40%) and high (60%) Quality levels. The analysis concludes that there are three factors that have major impacts on the viability of Outsourcing. First, when the volume of work to be accomplished is high, Outsourcing of engineering design is a viable option. However, as the complexity of the design increases, outsourcing of engineering design becomes increasingly less attractive. Finally, the analysis found that supplier quality is critical to successful outsourcing. Outsourcing to regions with low labor rates is attractive for labor cost reduction, but do not solve the problem of poor supplier quality with negative impact on Lead Time.

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Charles Ufongene

1. Introduction

1.1. Thesis Motivation

The Outsourcing of manufacturing is well-established in most industries, and is generally driven by a number of factors that include anticipated cost and schedule advantages and acquisition of a technology or expertise that the **OEM** (Original Equipment Manufacturer) may not have In-house, etc [1].

In the traditional manufacturing outsourcing Supply Chain model called **Contract Manufacturing (CM)** [2], a supplier receives completed product designs from an OEM and would simply focus on manufacturing, and, perhaps some packaging and assembling. Because the supplier firms simply manufacture products based on designs created by the OEM, the CM model is often referred to as "Build to Print."

Recently however, Outsourcing has also begun trending increasingly towards **Contract Design & Manufacturing (CDM)** in which the Supplier would also design a product, component or subsystem based on specifications provided by the OEM and would then also perform all of the traditional **CM** functions [3]. The supplier now both designs as well as manufactures the product or subsystem. **CDM** is fueled by the strategic objective of many OEMs to position themselves increasingly as Systems Integrators, with more focus on their customers. However, unlike product manufacturing where the Contract Manufacturing is based on a fixed product design, System Design is an iterative process, resulting in the generation of Engineering Change (EC), also called Design Change.

EC is the critical factor in determining Lead Time and the Labor cost of an Engineering Design work. The generation of Rework or EC depends on several factors including: Quality, Design Complexity, Time to Discover Rework, Time for Issues Resolution, Hiring New and less experienced staff and Overtime work.

The motivation of this thesis is to develop a Systems Dynamics model which incorporates anticipated risks factors associated with Engineering Design work to enable the simulation of their impacts on Lead Time and Labor costs. Since these factors exhibit wide variability when the Design is accomplished In-house compared to when it is outsourced, the model can therefore be used by an OEM for the Strategic Analysis of options in the sourcing of Engineering Design work.

1.2. Thesis Statement & Primary Research Objectives

The aim is the development of System Dynamics model directed at answering concrete, specific and important questions related to the decision-making on the sourcing of Engineering Design. For example, if a company is faced with a schedule deadline it estimates it cannot meet due to capacity constraint, then it may tactically outsource the design work to a supplier just to meet the target deadline. On the other hand, the company may strategically decide to outsource design work based on a technology it does not have in-house, and which it believes its supplier can perform more cost-effectively.

In any of the above scenarios there are several variables that impact the cost and schedule of the design effort and can result in remarkably different outcomes depending on whether the design is done in-house – where the Integrated Product Teams (**IPTs**) are typically co-located or outsourced to a supplier – in which case the IPTs are not co-located but distributed.

If the company is faced with a capacity constraint, it might first explore overtime and hiring strategies to address the problem before embarking on outsourcing. The downside of an overtime strategy is that over an extended period of time, the performance of overtime staff deteriorates due to tiredness leading to increase lack of concentration which in turn impacts both Productivity and Quality negatively. If a hiring strategy is adopted, then the company is faced with significantly reduced performance from the new hires due to inexperience which again negatively Productivity and Quality of the design work leading to increased cost and schedule overruns.

Before the company makes the decision to outsource a design work, it will need to fully investigate the impact that EC (Engineering Change) would have on the cost and schedule of the process. Designing a new system or product is an iterative process, making Design Changes inevitable. When the design work is done in-house, because the IPTs are typically co-located which enables the Engineers to communicate more frequently, design defects would tend to be detected sooner and fixed. Moreover, since it is the same company, Issues Resolution although typically formalized can still be resolved rather quickly. When the design work is outsourced, it would typically take longer time to detect errors because the Engineers of the OEM and the supplier company are typically at different locations and therefore communicating less. Even more important is the fact that when such defects are discovered, rectifying them may well require a Contract Change – thereby dragging out the design process. This has a huge impact on both cost and schedule. It might therefore come as a surprise to the OEM that the delays associated with design defects discovery and Issues Resolution might end up being the dominant factors that determine duration and cost when design is outsourced – despite the fact that the supplier company is perceived to have no capacity constraints.

The Primary Research Objectives of this work is to:

- Develop a System Dynamics model that can be used to simulate the dynamics of various factors that impact the generation of EC – and consequently Lead Time and Labor cost.

- Employ the model to study the impact of overtime work and hiring on Quality and Productivity – which in turn impact the generation of EC, Lead Time and Labor cost.

- Employ the model to study the impact of Quality, Productivity, Time to Discover Rework, Time for Issues Resolution, Design Complexity, Volume of Design work to be done, on the generation of EC, Lead Time and Labor cost.

- Employ the model in the decision making about the sourcing of Engineering Design work.

The analysis looks at options for sourcing of Engineering Design work. In order to investigate the impact of EC on Engineering Design Lead Times and Labor costs, the model employs a number of factors which impact the generation of EC as exogenous variable to study the dynamics of EC on Lead Times and Labor cost. These factors include: Quality, Design Complexity, Time to Discover Rework, Time for Issues Resolution, Hiring new and less experienced staff and Overtime work. To enable an OEM make informed decision about sourcing a particular Design work, we employ the model to analyze an example case in which an OEM faced with a staff capacity constraint because it has only 50% of the staff needed to finish the Engineering Design work explored its options as follows:

- Adopt an Overtime Strategy
- Adopt a Hiring Strategy
- Adopt a combination of Over Time and Hiring Strategy
- Adopt an Outsourcing Strategy

1.3. Impacts of Outsourcing Engineering Design Work

The Outsourcing of engineering design has a number of potential disadvantages which include:

- Costly design change processes & loss of flexibility in product redesigns: It is a well established fact in Product Development that complex products and systems typically require several design iterations. When the Design is accomplished In-house, then design changes could be managed more flexibly and informally – resulting in lower costs.

- Under the CDM model, any design changes will have to be formalized between the OEM and its suppliers. In some cases, these Design Changes could have an impact that would require a contract change making the design change process sometimes contentious, time-consuming and costly.

- If the design of major subsystems and components are subcontracted, there is the potential risk when O & R (Overhaul & Repairs) are needed, customers may try to bypass the OEM and go to procure such parts directly from suppliers at cheaper rates. In an Aerospace OEM, the impact on O & R could be huge given that O & R is a major source of revenue stream for the aircraft OEMs.

- In the future, major subsystem suppliers would have enough leverage over the OEM to insist on being co-bidders for contracts – since technology know-how would increasingly lie with the suppliers leaving the OEM increasing vulnerable.

- OEMs positioning themselves merely as System Integrators while increasingly outsourcing design and manufacturing raises a serious supply chain problem. How well or effectively can the OEMs manage their various suppliers to ensure that schedules are met?

- Under the CDM model, there is a potential risk of loss of valuable intellectual property (IP), first to the supplier – then subsequently passed on to the competition.

Many Contract Manufacturers, especially in the Electronics industry have morphed into **ODMs** (Original Design Manufacturers) [4] by initially learning the art of product design from the OEMs, and subsequently coming up with their own design which they can then market to any OEM for Branding [5, 6]. The main distinction between CDM and ODM models is that under the CDM model, the product is manufactured based on the design of the OEM. Under the ODM model, the Contract Manufacturer also owns the product design. The OEM merely brands the product.

1.4. Engineering and Management Content

Systems Dynamics modeling will use in analyzing the impact of CDM on Quality, cost and schedule. The results of the modeling can enable management to make informed decisions

1.5. Research Methods & Approaches

We will develop a highly parameterized model in which pertinent factors are exogenous variables, and then analyze the dynamics of the impact of the various parameters on Quality, Productivity, the generation of EC, cost and schedule.

1.6. Thesis Outline

- Chapter 2 discuss the key drivers for Vertical Integration and Outsourcing.
- Chapter 3 is the development of the System Dynamics Model
- In Chapter 4 the model is calibrated to a real Engineering Design case as Baseline. The model is then employed to simulate the dynamics of the various parameters to investigate their impact on Quality, Productivity, Engineering Leads Time and Labor Costs.
- In chapter 5 we simulate the Dynamics of Sourcing Engineering Design by investigating the impacts of the various factors in the context in which the design work is accomplished In-House and the context in which the Engineering Design is Outsourced.
- In chapter 6 we employ the results of Chapter five to develop strategies for the sourcing of Engineering Design
- In chapter 7 we present the conclusions recommendations

2. Key Drivers for Vertical Integration & Outsourcing

2.1. Introduction

The outsourcing of manufacturing – typically called CM (Contract Manufacturing)- is well established in several industries, including Electronics [7, 8] and Aerospace [9]. The justification for the outsourcing of manufacturing was based on the fact that many OEMs do not look to manufacturing to distinguish themselves from the competition. The outsourcing of manufacturing was driven by a number of factors, including:

- The OEMs view product design and marketing as the areas that enable them to differential their products, and thus the outsourcing of manufacturing (product production) enabled the OEMs to concentrate on their core competencies. Similarly, the manufacturing experience gained by the supplier companies enabled them to produce more efficiently – either at lower cost or with shorter lead times – compared to the OEMs

- Outsourcing enabled the OEMs to take advantage of "Economies of scale" to reduce their manufacturing costs. This happens as follows: because the contract manufacturing company serves multiple OEMs for the production of similar products, the contract manufacturer could leverage fixed asset more efficiently than individual OEMs. Moreover, as a result of the multiple OEMs served the contract manufacturer often require raw material and components in large volumes. This gives the contract manufacturer the leverage to negotiate price reduction from their own suppliers – resulting in lower production costs for the multiple OEMs served.

- Outsourcing enabled the OEMs that have global presence to take advantage of the global footprint of the contract manufacturer that often had worldwide presence with manufacturing facilities spread across multiple countries and regions of the world. This therefore mitigates the risk to the OEMs if they were compelled to concentrate their manufacturing capacity in limited geographic areas.

- While cost is still the major driver in outsourcing, there are other important considerations such as proximity to the market in such places as China and India that is forcing OEMs to outsource to those countries. Some OEMs also view China and India as having large talent pools that they can tap into to address capacity constraints.

However, recently OEMs have also started the outsourcing of R&D and Engineering Design [10, 11, 12, and 13]. The decision by many companies to outsource or vertically disintegrate is driven by the desire to gain competitive advantage by keeping abreast with technological change and gaining new technology and capacity cheaply via suppliers.

- One of the drivers of this R&D shift overseas is the rise of virtual prototyping. The ability to design and test machines on a computer has made design work more mobile.

- Also, it is advantageous to locate R&D in places such as India and China - in close proximity to these emerging market.

2.2. The Vertical Integration Decision Making

Vertical integration is a measure of how much control that a company – the OEM, has over its inputs and the distribution of its products and services. There are two types of Vertical integration: (i)-Backward Integration – in which a company acquires its suppliers in order to reduce risk of dependency; improve performance/processes, etc and (ii) Forward Integration – in which a company becomes more customer-focused by expanding its activities to include control of the direct distribution of its products. Some of the benefits of Vertical integration include: Economies of scale, Economies of scope, Cost reduction, Competitiveness, Reduced threat from powerful Suppliers and Customers and Higher degree of control over the entire Value Chain [14].

The decision to vertically integrate as opposed to outsource, is a fundamental decision a confronting a company. As discussed extensively in [15], because of the fact that all industries, products and the market place are in a state of constant change, the vertical integration decision is a strategic question that confronts a company on a continuing basis. To answer the vertical integration question, an OEM must therefore make a decision about:

- How much of the value chain it plans to keep In-House. In other words, what are the core functions or activities that the company should perform In-House. Once the determination is made about what activities to keep In-House, the next question confronting the OEM is to determine whether or not it has the required capacity, technology know-how, etc to satisfy all of its internal demand, or make the decision to outsource part of the activities otherwise.

- Under what conditions should the company change the amount of the value chain it keeps In-House – and in what direction should the changes be made – integrating Backward towards its suppliers or integrating Forward towards its customers?

A number of factors are necessary in making the vertical integration decision and include:

1. Strategic factors – including the determination as to whether or not an activity is deemed critical to development or sustenance of the core capabilities that the company wants to keep for In-House [16].
2. Market factors – which deals with the dynamics of the industry in which the company is playing [17].

3. Product, Service and Technology factors – which relates technology, product or service architecture and product or service development to Operations [18].
4. Economic factors – which balances the cost of keeping an activity In-House to the cost of Transacting for that activity alternatively [19].

2.3. Strategic factors in Vertical Integration Decision Making

In an ideal scenario where supplier markets are perfectly reliable and efficient, a company would rationally choose to keep In-House only those capabilities that enable it to achieve competitive excellence/advantage and would outsource all other activities. In order to make the vertical integration decision, an OEM first needs to clearly identify what it considers its core capabilities. In practice, these core capabilities will also need to be dynamic and changing over time in response to the dynamics of the market in which a company operates as well as its products space which are also dynamic and changing with time. The determination as to whether or not an OEMs core capabilities must be retained In-House for them to remain core is the vitally important first step in making the vertical integration decision.

Core capabilities may be defined as the set of activities – including skill and systems - that an OEM excels in performing, or is assumed to perform better that its competitors which therefore gives the company the competitive advantage. Core capabilities enable a company to create uniquely high value for its customers, and do not derive independently from individual skill sets or systems, but from their integration. Since the operational environment is dynamic and always changing, a company's core capabilities must therefore be non static and flexibility to accommodate both current and future requirements.

As a rule-of-thumb for making the vertical integration decision, if an OEM considers an activity critical to its future success, then the OEM needs to retain or develop such activity In-House, or alternatively enter into close alliances with suppliers providing that activity. The vertical integration decision making also needs to take other factors such as Cost, Quality, Availability and Features/Innovativeness into consideration. As an example, if Availability is the basis of the competition, in which case a high level operational flexibility is required, then the OEM may opt to outsource that activity to avoid being saddled with assets it cannot easily find use for in case of severe demand downturns.

On the other hand, if cost is the basis of the competition, then the OEM may decide to outsource to allow its suppliers gain economies of scale since such suppliers typically perform similar contract jobs for other companies – resulting in higher volume and cost efficiencies for the OEMs and the supplier, compared to each individual OEM performing that activity on their own. This was indeed the basis of the growth in CM in the Electronics industry where EMS (Electronics Manufacturing Service) companies performed manufacturing tasks for several OEMs based on the designs of the OEMs in what came to be known as "Build to Print" [20, 21]. An OEM may also decide to vertically integrate in order to get a handle on Cost, Quality, Availability and Features/Innovativeness.

There may also be scenarios in which an OEM finds it impossible to develop a core capability as quickly as needed. This may indeed be the case when for example the OEM is pursuing new market opportunities and is faced with capacity constraints, or when a new product requiring the technical know-how in a new technology that the company does not currently have or is deficient in. In such situations therefore, the OEM, in order to gain access quickly to the new technology or capacity in the short-run outsources that activity to suppliers with the requisite competent in the short run. This has the effect of enabling the OEM to gain the time to develop the skills or increase capacity internally. Strategically, a company ideally owns only the activities it deems core and critical to its operations – all non core activities are candidates for outsourcing. On a tactical basis, a company may decide to outsource a core activity in the short term.

2.4. Market factors in Vertical Integration Decision Making

There are three major market factors to be considered when making the vertical integration decision: Market Reliability, Economies of Scale; and Asset Specificity and Dependency Risk.

- Market Reliability (Supplier Performance) – This is the ability of a supply base to achieve high performance in terms of Cost, Quality, Availability, Features/Innovativeness and Environmental requirements. This is based on the premise that when there are many suppliers competing to provide a product or service to an OEM, the advantage to the OEM in not outsourcing that product or service diminishes for a number of reasons: Firstly, the fierce competition among the suppliers fosters high performance, leading to lower costs and better quality products. Secondly, if a company considers an activity as non-core activity, there is general lack of interest in that activity leading to under-funding and decreasing performance in that activity within the company. Therefore, the superior performance that suppliers can offer due to the fierce competition in their space is a key driving force in the outsourcing of non-core functions. However, there are also instances where the supplier has severely underperformed in terms of Cost and Quality. In such cases, the OEM may decide to vertically integrate in order to improve performance.

- Economies of Scale – A supplier providing similar product or service to several OEMs would typically have lower unit cost for the product/service when compared to each of the OEMs the supplier serves providing such product or service for themselves. This is because the supplier benefits from an increased volume production by aggregating demand from all the companies it serves resulting in lower unit cost, or the Economies of Scale. Economies of Scale is a strong driving force for outsourcing because companies are made aware of the fact that their suppliers can achieve lower production cost than they simply because the supplier produces such product in greater volumes.

- Asset Specificity and Dependency Risk - Dependency Risk means that either the OEM or its supplier is compelled to adapt its product or service in some way to accommodate the requirements of the other party's product or service. A supplier may for example retool its machines just to accommodate the unique design requirements of an OEM customer. An OEM and its supplier may decide to co-locate their facilities just to cut on transportation lead times, cost, etc. These sort of special arrangements means that there is some degree of Asset Specificity in the relationship in which the company and /or its supplier invest in assets, to include people/training (Human Capital Specificity) , technology, equipment (Dedicated Assets) and physical facilities (Physical Asset Specificity) to better serve the other party's needs. The disadvantage is that such assets so deployed, are not easily transferable to the needs of other customers – should alliances change. The higher the degree of Asset Specificity in an OEM – supplier relationship, the higher the dependencies or interdependencies and the greater the degree of vertical integration. The vertical integration decision also needs to take into account the frequency of transactions between the OEM and its supplier. When both the frequency of transactions and the degree of Asset Specificity are high, then vertical integration makes more sense

2.5. Product, Service and Technology factors in Vertical Integration Decision-Making

The Vertical Integration Decision-Making needs to consider Product, Service and Technology factors and how IP (Intellectual Property) is impacted.

- **IP:** When an OEM outsources the activities associated with a critical technology, there is a distinct risk that the critical technology will eventually find its way to competitors via the common supplier who acquired the technology from the OEM – who may as a consequence lose its competitive edge due to the loss of this critical technology. Therefore, IP considerations are a critical factor in making the decision to vertically integrate versus outsource. If the decision is made to outsource, then the OEM must take special care to protect its IP in any transactions with its suppliers.

- **Technology Differentiation:** Vertical integration can be used by a company to foster technological differentiation with its competitors. On the other hand, vertical integration can render a company too rigid and inflexible, making if harder for the company to quickly adapt to or take advantage of a new technology in a dynamic and changing operational environment. The first question a company needs to ask in matters of technology is whether or not it considers a particular technology as core to its operations. If the answer is in the affirmative, then the company must be ready to invest in R&D to enhance its position and know-how in the specific technological area. If the technology currently exists but outside the company, then the company should seek ways of forming alliances with suppliers in order to access the technology.

- **Modular Architecture:** In a modular product architecture, each component plays a separate role or function, with a one-to-one mapping between the components and those functions. Modular product architectures makes it easier to vertically disintegrate parts towards suppliers and makes products more easily serviceable and easier to maintain by swapping parts – but result in decreased performance versus Integral architecture. Modular product architecture also has a huge impact in maintenance, Overhaul & Repairs. In the aircraft industry for example, maintenance, Overhaul & Repairs represents a major source of revenue. The disadvantage of the modular architecture for aircraft industry OEMs is that it opens the possibility of their customers going directly to suppliers who manufacture the different aircraft parts/subsystems to procure parts – as opposed to going through the OEMs.

- **Integral Product Architecture:** In an integral product architecture, there is a one-to-many mapping between components and functions. Integral Product Architectures are used mainly to enhance product performance. Integral Product architecture makes it easier to vertically integrate, and more difficult to outsource. The advantage of the Integral architecture for aircraft industry OEMs is that it gives the OEMs more control over their customers in matters of maintenance, Overhaul & Repairs.

2.6. Economic factors in Vertical Integration Decision Making

This involves analyzing the economics – including Transaction, Coordination and Transportation costs - of carrying on an activity In-House versus outsourcing it.

- **Investments Cost** – Cost associated with the decision by a company to acquire or develop a capability In-House which could be capital costs (includes equipment and facilities costs); people costs (includes labor and training costs); System development and Inventory costs. Acquisition of a capability could also mean the acquisition - in whole or in part - of another company that already possesses that capability. Conversely, if the company decides to vertically disintegrate a capability, it would outsource the activity associated with that capability, or divest part of it associated with that capability.

- **Design, Production & Delivery Costs** – These are the cost incurred by a company for the design, production and delivery of a product or service. If an OEM chooses to vertically disintegrate the activity associated with the design, production and delivery of a product or service to a supplier, then the OEM will have to cover the cost to its supplier for design, production and delivery (to the OEM location) of the product or service, including the supplier profits. When the OEM and its supplier are located in the same geographic area, labor cost, which constitutes a major part of the cost, are typically similar. The pertinent question then is the following: how then is it possible for the supplier to provide the same activity at a lower overall cost that the company?

  Firstly, when the activity involved is production, since a supplier typically provides the same type of service – in this case, manufacturing - to several OEMs, the supplier achieves economies of scale which lowers the supplier's unit cost of production. Second, when the activity involved is Design, then the supplier possesses a pool of workforce that is highly skilled in the Design of given systems/products – enabling the supplier to accomplish the Design tasks with higher *Quality* and *Productivity* than the OEM – resulting in lower Engineering Design Lead Time and Labor Cost. The impact of *Quality* and *Productivity* on Engineering Design Lead Time and Cost is quite profound, and as the Systems Dynamics Model Analysis and Simulations in this Thesis will show, if the OEM and its supplier have the same labor rates, then Outsourcing makes sense *Only if* the supplier performs the activity at a higher *Quality*.

Delivery Costs are becoming increasing complex to analyze. In the Aerospace Industry for example, the major manufacturers Boeing and Airbus Industrie, France are increasingly morphing into System Integrators and are skillfully reducing Delivery Costs by moving aircraft subsystems from one supplier location to another for integration – as opposed to transporting all the subsystems to manufacturers' location. Only what is terms 'Final Assembly' – that is, putting together few large sections of the aircraft - is done at Airbus [22]. Boeing is also moving in that direction with the 787 Deamliner [23].

- **Issues Resolution or Transaction Costs** – When a company decides to outsource a design work, Transaction costs are uncertain and often very significant. In the normal course of events, when a company outsources a design work, the details of the work to be accomplished by the supplier are defined in the Requirements which form the basis of a contract between the two parties. However, in the course of executing the design work, issues typically arise where the company disagrees with the supplier's interpretation of a requirement, and initiates a Design Change request. The supplier on its part may determine that such Design Change request initiated by the company is tantamount to a Contract Change and indeed demand such a Contract Change. This could grow quite contentious, bringing back attorneys to the table to figure it out. In the meantime this could holdup Engineering work which has a very negative impact, not just on Labor cost but also on Lead Time. Issues would still arise if the company were to vertically integrate the design work, but the Issues Resolution will typically take much shorter time because there is no risk of the EC impacting a contract – as would be the case when two separate legal entities such as the OEM and the supplier are involved.

In summarizing, it must be stated that the vertical integration question is quite complex, requiring very careful consideration. For example, vertically integrating an activity while solving a specific problem may in fact create new ones for the OEM. The quantitative analysis methodology such as presented in this thesis work are only part of the tool to enable management make informed decision. The vertical integration decision should be made based on both qualitative and quantitative analysis.

3. System Dynamics Model Development

3.1. Introduction

In this chapter we develop the System Dynamics Model for use in the Analysis. A set of Exogenous variables is shown in Table 3.1 which are input to the system, enabling the simulation of the dynamic behavior of the Endogenous variables shown in Table 3.2. An Exogenous variable may be defined as an independent variable and is therefore external to the model. However, a change in an exogenous variable produces a change or impact on the endogenous or dependent variables [24]. Exogenous variable are so-called because their values are independent and are not determined by other parameters and variables in the model, but are externally set and any changes to their values come externally.

Endogenous on the other hand means originating or arising from within. A variable is termed endogenous in a model if its value depends on other variables. In other words, an endogenous variable is a function of at least one other variable in a model – hence an endogenous variable is a dependent variable.

Therefore, by varying such exogenous variables as *Mean-Time-to-Discover-Rework, Ref-Quality, Ref-Productivity, Design Complexity, Staff Capacity, Time-for-Issues-Resolution,* etc as shown Table 3.1 we can study the dynamics of their impact on such Endogenous or dependent variables as *Quality, Productivity, Engineering-Design-Lead-Time, Labor costs, etc.*

Table 3.1: Model Exogenous Variable

No	Variable name
1	*Ref-Quality*
2	*Ref-Productivity*
3	*Design-Complexity*
4	*Initial-Numb-of-Design-Work-to-Do*
5	*Mean-Time-to-Discover-Rework*
6	*Time-for-Issues-Resolution*
7	*Minimum-Time-to-Perform-a-Design*
8	*Relative-Quality-of-New-Hires*
9	*Relative Productivity-of-New-Hires*
10	*Staff-Capacity*
11	*Numb-of-Experienced-Staff*
12	*Over-Time-Staff Capacity*
13	*Over-Time-Quality-Decrease-Rate*
14	*Over-Time-Productivity-Decrease-Rate*
15	*Hiring-Rate*
16	*Time-for-New-Hires-To-Gain-Experience*

Table 3.2: Model Endogenous Variable

No	Variable name
1.	*Quality*
2.	*Productivity*
3.	*Rework Discovery Rate*
4.	*Rework Generation Rate*
5.	*Undiscovered Design Rework*
6.	*Numb of Design Work Completed*
7.	*Engineering-Design-Lead-Time*
8.	*Relative Quality of New Hires*
9.	*Impact of Experience & Over Time On Quality*
10.	*Quality of Over Time Staff*
11.	*Change in Quality of Over Time Staff*
12.	*Over Time Quality Decrease Rate*
13.	*Relative Productivity of New Hires*
14.	*Productivity of Over Time Staff*
15.	*Change in Productivity of Over Time Staff*
16.	*Over Time Productivity Decrease Rate*
17.	*Impact of Experience & Over Time On Productivity*
18.	*Hiring Rate*
19.	*Numb of New Hires*
20.	*Numb of Experienced Staff*
21.	*Additional Staff Required*
22.	*Cum Design Work Done*
23.	*Numb of Engineering Changes (EC)*
24.	*Numb of Design Work to Do*
25.	*Time to Discover Design Rework*
26.	*Initial Numb of Design Work to Do*
27.	*Design Rework Discovery Rate*
28.	*Design Rework Generation Rate*
29.	*Current Staff Level*
30.	*Numb of New Hires*
31.	*Numb of Experienced Staff*
32.	*Rate of New Hires Gaining Exp*
33.	*Initial Numb of Exp Staff*
34.	*Cum Labor Cost*

3.2. Modeling Fundamentals

In this section we develop an initial System Dynamics model. Figure 3.1 shows the Level variables *Numb-of-Design-Work-to-Do* and *Numb-of-Design-Work-Completed* which are linked by a Rate variable *Design-Work-Accomplishment-Rate* [25]. The *Numb-of-Design-Work-to-Do* has an initial value of *Initial Numb-of-Design-Work-to-Do.*

As we begin to accomplish the design work, the variable *Numb-of-Design-Work-to-Do* begins to decrease from its initial value while the variable *Numb-of-Design-Work-Completed* begins to increase from initial value of zero.

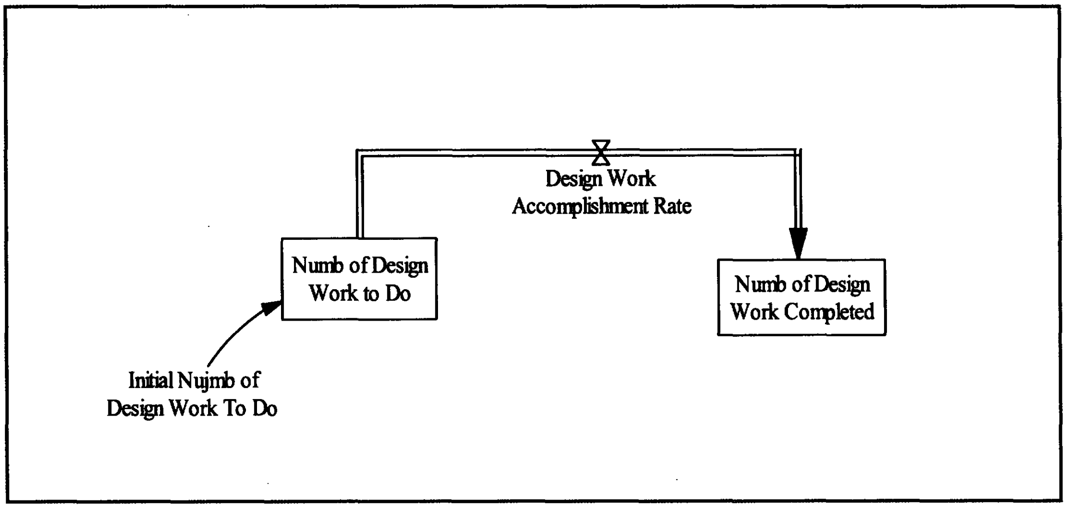


Figure 3.1: The basic Work Accomplishment Model

The rate at which the variable *Numb-of-Design-Work-to-Do* is being drained and the *Numb-of-Design-Work-Completed* being filled is determined by the Rate variable *Design-Work-Accomplishment-Rate.* This enables us to represent the dynamics of the design work completion rate by the following pair of time-dependent differential equations:

$$\frac{d(Numb\ of Design\ Work\ to\ Do)}{dt} = -(Design\ Work\ Accomplishment\ Rate) \qquad 3.1$$

and

$$\frac{d(Numb\ of Design\ Work\ Completed)}{dt} = Design\ Work\ Accomplishment\ Rate \qquad 3.2$$

Integrating the above equations over the interval $0 < t \leq T$ yield the follow pair:

$$Numb\ of Design\ Work\ to\ Do$$
$$= Initial\ Numb\ of Design\ Work\ to\ Do - \int_0^T (Design\ Work\ Accomplishment\ Rate)dt \qquad 3.3$$

and

$$Numb\ of Design\ Work\ Completed = 0 + \int_0^T (Design\ Work\ Accomplishment\ Rate)dt \qquad 3.4$$

Where T is the time duration of the transfer process during which *Numb-of-Design-Work-to-Do* is drained empty, and the *Numb-of-Design-Work-Completed* is filled– indicating that we have no more design work left to accomplish.

Typically, the equations 3.3 and 3.4 are solved numerically using Euler or Rungi-Kutta Numerical Integration methods in Vensim software [26].

3.3. The Rework Generation Loop

The above analysis assumes however, that the work was being accomplished with perfect *Quality* – that is, no defects were being generated as the work was being accomplished. In reality however, defects are almost always generated as part of the design process, and the percentage of the defect in the completed work determines the *Quality* or efficiency with which the design work was being accomplished.

Therefore, we introduce a modified model as in Figure 3.2 to include a loop for Design Rework [27]. Note that at each iteration during the design process, the *Numb-of-Design-Work-to-Completed* is composed of both work perfectly accomplished and work defectively accomplished.

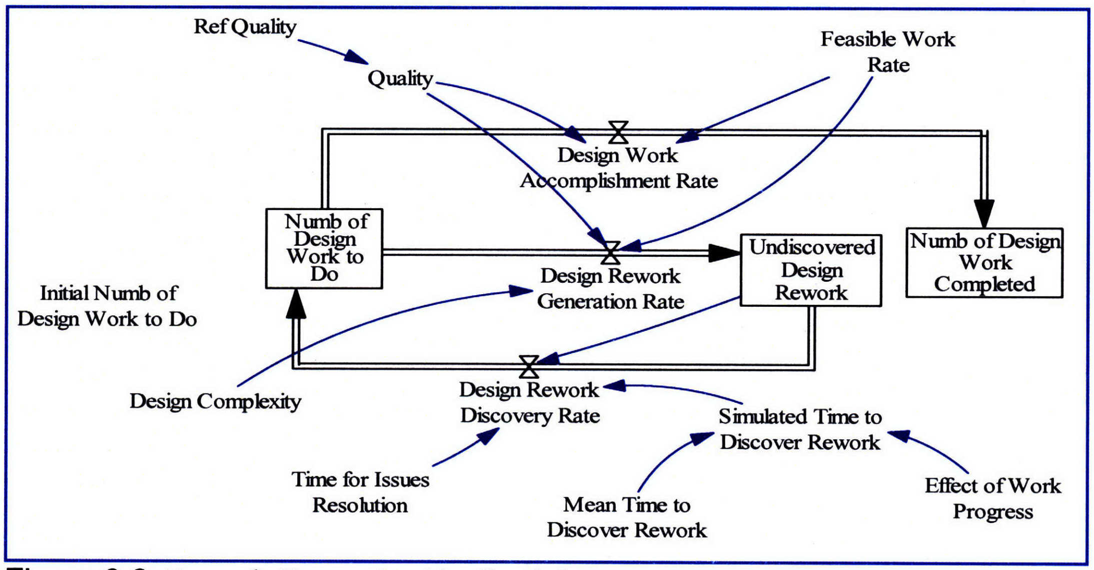


Figure 3.2: Rework Generation Feedback Loop

However, work defectively accomplished must be sent back to the pool of the variable *Numb-of-Design-Work-to-Do* to be Reworked. We therefore introduce the feedback loop [28] to cycles back defectively accomplished work into the variable *Numb-of-Design-Work-to-Do* as shown via the new variables: *Design-Rework-Generation-Rate, Undiscovered-Design-Rework* and *Design-Rework-Discovery-Rate.*

Hence eqn. 3.3 is modified as follows:

$$\mathit{Numb\ of\ Design\ Work\ to\ Do}$$
$$= \mathit{Initial\ Numb\ of\ Design\ Work\ to\ Do} - \int_0^T (\mathit{Design\ Work\ Accomplishment\ Rate} - \mathit{Design\ Rework\ Generation\ Rate})\,dt \qquad 3.5$$

This is accompanied by the following Quality-dependent pair of equations:

$$\mathit{Design\text{-}Work\text{-}Accomplishment\text{-}Rate} = \mathit{Feasible\text{-}Work\text{-}Rate} \times \mathit{Quality} \qquad 3.6$$

$$\textit{Design-Rework-Generation-Rate} = \textit{Feasible-Work-Rate}(1-\textit{Quality}) \qquad 3.7$$

$$\textit{Design Rework Discovery Rate} = \frac{\textit{Undiscovered Design Rework}}{\textit{Simulated Time to Discover Rework} + \textit{Time for Issues Resolution}} \qquad 3.8$$

$$\textit{Undiscovered Design Rework} = \int_0^T (\textit{Design Rework Generation Rate} - \textit{Design Rework Discovery Rate})dt \qquad 3.9$$

3.4. The Quality Loops

Quality has been variously defined depending on the context. For example, the Web Dictionary, - WebDictionary.co.uk - defines Quality as a measure of excellence or of worth. For the purpose of this analysis, we define Quality here as the percentage or fraction of the completed designs at each pass of the design iteration that conforms to the design specifications. Designs work that do not meet the specification requirements are deemed defective and result in Engineering Change or Reworked. As was mentioned in the foregoing, Engineering Change can result either from a design revision aimed at improving system performance, etc or from a defect correction. In order not to lose sight of the big picture, this analysis has avoided making the distinction between design revision and defect correction. Widely used industry Quality metrics include Six Sigma, TQM (Total Quality Management), Zero Defects, etc [29].

As shown in Figure 3.3, factors that impact Quality include: *Ref Quality*, Overtime Work, the Effect of Prior Work Quality On Quality, and level of Experience of the staff. *Ref Quality* is the exogenous variable that defines the Quality of work performed by an experienced staff. Note importantly that *Quality* is a dependent or endogenous variable whose dynamics depends on the four factors presented above. Thus *Quality* is modified from an initial value of *Ref Quality* as a result of Overtime Work, the Effect of Prior Work Quality, etc.

From Figure 3.3, if only experienced staff working straight hours are considered, then Quality is given by:

$$\textit{Quality} = (\textit{Ref Quality})(\textit{Effect of Prior Work Quality on Quality}) \qquad 3.10$$

However, the impact of New Hires and Over Time work on Quality modifies the equation to:

Quality=
(Ref Quality)(Effect of Prior Work Quality on Quality)(Impact of NewHires & OverTime OnQuality)

3.11

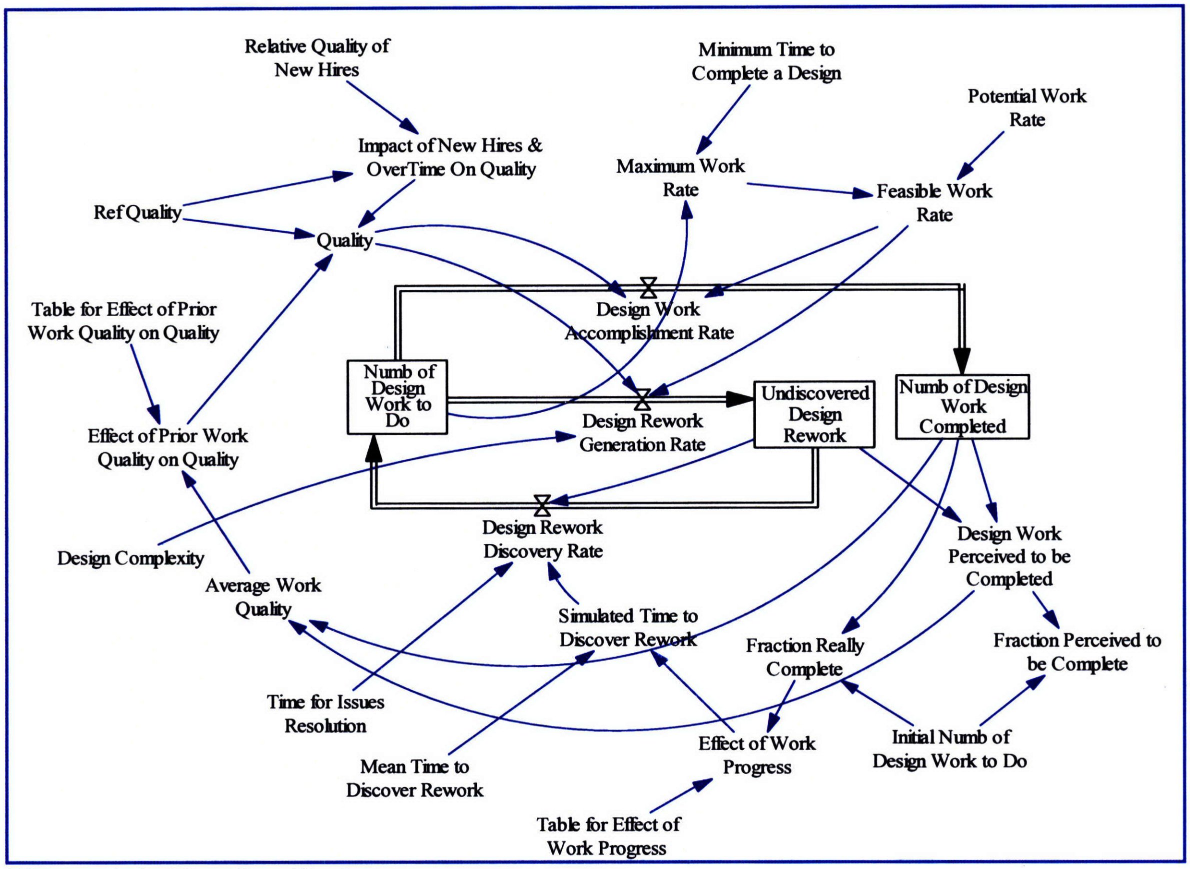


Figure 3.3: The Quality Loop

3.5. The Productivity Loops

As with *Quality*, *Productivity* has been variously defined. Productivity is the amount of output produced relative to the amount of resources (time and money). Productivity may therefore be expressed as the ratio: Output quantity/Input quantity [30]. In this analysis, Productivity is defined as the Number of Designs performed by a person (or staff) per day. It therefore has the units of Number of Designs per Person-Day. Again as with Quality, *Ref Productivity* is the exogenous variable that defines the Number of Designs accomplished by an experienced staff per Day. Two variables impact Productivity – Overtime work and lower relative productivity of new Hires, both of which decrease Productivity because of tiredness (in case of Overtime work) and lack of experience (in case of new hires). We thus see that Productivity is an endogenous variable which is modified from *Ref Productivity* as a result of Overtime work and new hires. If only Experienced staff working straight hours are considered, then from figure 3.4 *Productivity* is given by:

$$Productivity = Ref\ Productivity \qquad 3.12$$

However, the impact of New Hires and Over Time work on *Productivity* modifies the equation to:

$$Productivity = (Ref\ Productivity)(Impact\ of\ Experience\ \&\ OverTime\ On\ Productivity) \qquad 3.13$$

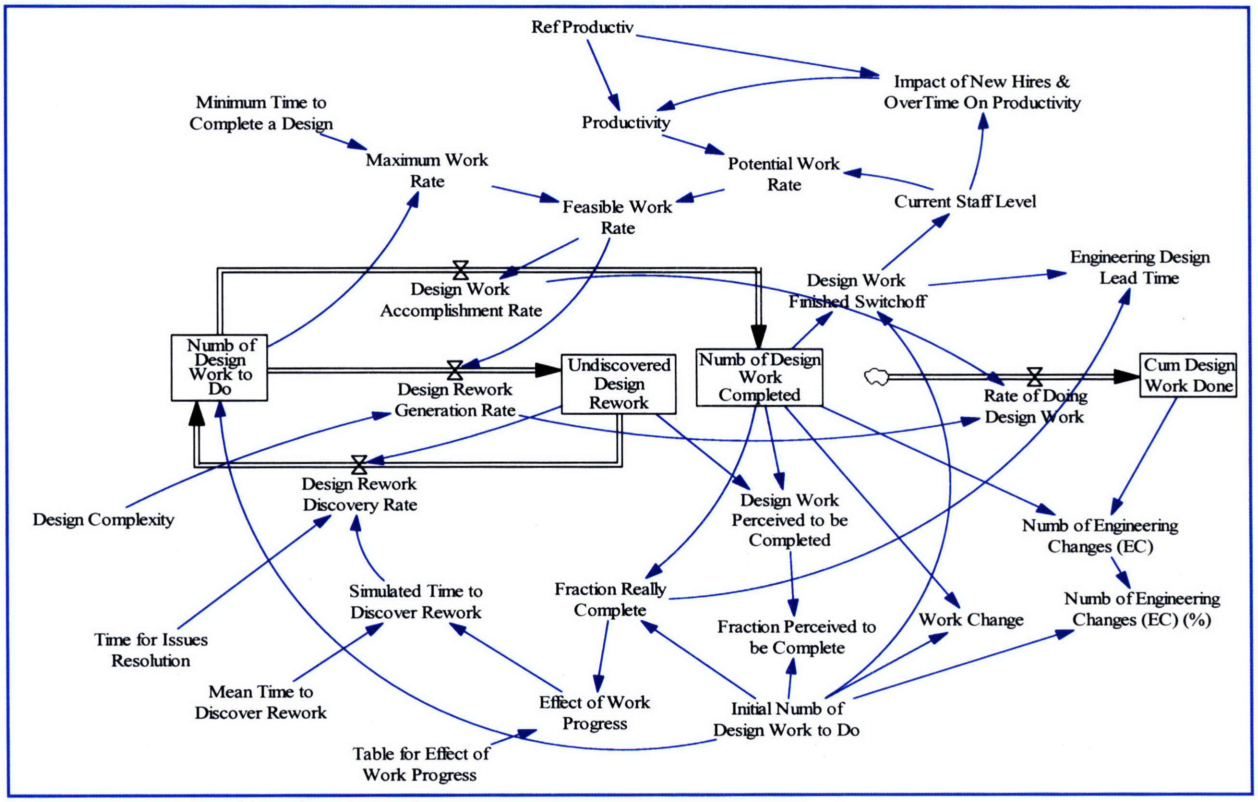


Figure 3.4: The Productivity Loops

3.6. The Over Time Loops

1.6.1. Impact of New Hires & Over Time On Quality

From Figure 3.5, this is given by:

$$Impact\ of\ NewHires\ \&Over\ TimeOn\ Quality =$$

$$\frac{(Numb\ of\ New\ Hires)(Relative\ Quality\ of New\ Hires) + Numb\ of\ OverTime\ Staff\left(\frac{Quality\ of OverTimeStaff}{Max\ Quality}\right) + Numb\ of\ ExperiencedStaff)}{Current\ Staff\ Level} \qquad 3.14$$

and

$$Quality\ of\ OverTime\ Staff = Ref\ Quality - \int_0^T (Change\ in\ Quality\ of\ Over\ Time\ Staff)dt$$

3.15

$$Change\ in\ Quality\ of\ Over\ Time\ Staff = \frac{Quality\ of\ Over\ Time\ Staff}{Over\ Time\ Quality\ Decrease\ Rate}$$

3.16

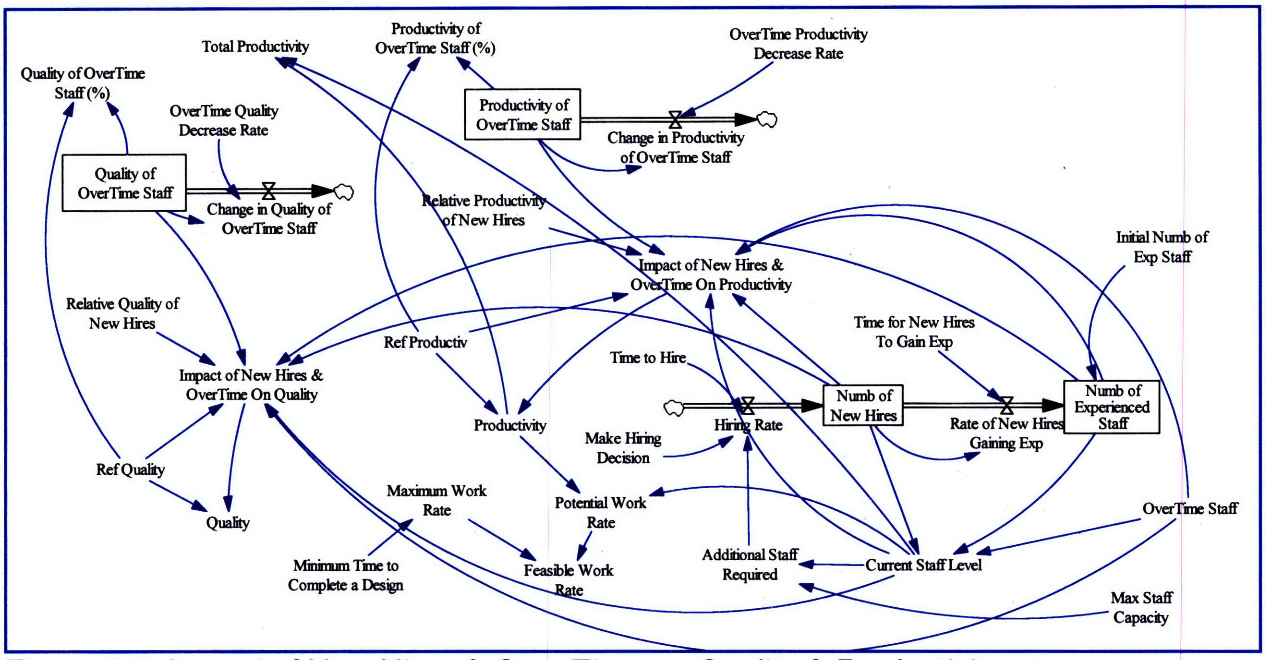


Figure 3.5: Impact of New Hires & Over Time on Quality & Productivity

1.6.2. Impact of New Hires & Over Time On Productivity

From figure 3.5, this is given by

$$Impact\ of New\ Hires \&\ Over\ Time\ On\ Productiv =$$

$$\frac{(Numb\ of\ New\ Hires)(Relative\ Productiv\ of New\ Hires) + Numb\ of\ OverTime\ Staff\left(\frac{Productiv of\ OverTime\ Staff}{Max\ Productiv}\right) + Numb\ of\ ExperiencedStaff)}{Current\ Staff\ Level}$$

3.17

$$Productivity\ of\ OverTime\ Staff = Ref\ Productivity - \int_0^T (Change\ in\ Productivity\ of\ Over\ Time\ Staff)dt$$

3.18

$$Change\ in\ Productivity\ of\ Over\ Time\ Staff = \frac{Productivity\ of\ Over\ Time\ Staff}{Over\ Time\ Productivity\ Decrease\ Rate}$$ 3.19

3.7. The Hiring Loops

In the last section, we discussed the impact of new hires on *Quality* and *Productivity*. In the current section, we derive the equations for the number of New Hires. Figure 3.6 shows the Hiring loop from which:

$$Numb\ of\ New\ Hires = \int_0^T (Hiring\ Rate)dt \qquad 3.20$$

However, as these new hires are getting trained, they gain enough experience to move from the New Hire staff category - with decreased *Quality* and *Productivity* – to the fold of experienced staff. Therefore, the number of new hires is modified as follows:

$$Numb\ of\ New\ Hires = \int_0^T (Hiring\ Rate\ -\ Rate\ of\ New\ Hires\ Gaining\ Exp)dt \qquad 3.21$$

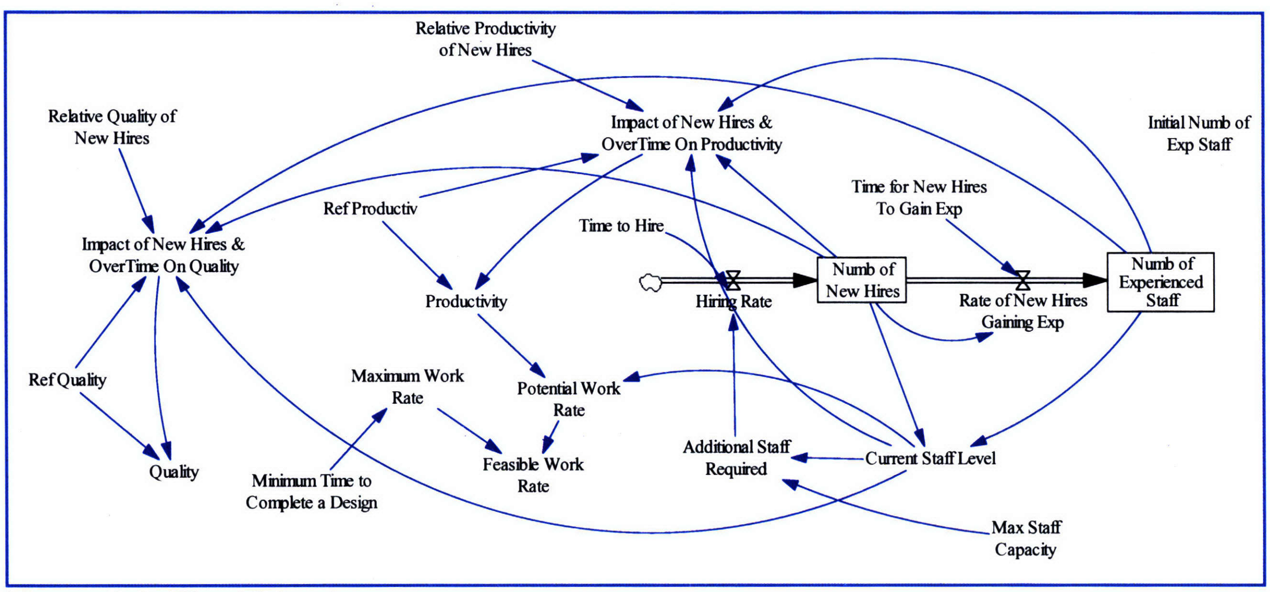


Figure 3.6: The Hiring Loops

where

$$Hiring\ Rate = \frac{Additional\ Staff\ Required}{Time\ to\ Hire} \qquad 3.22$$

3.8. Engineering Change (EC)

As discussed above, Engineering Change occurs as a result of imperfect or defective work quality, requiring rework and design iterations leading to revisions. Therefore, the cumulative work done is higher than the initial work to do because of the design revisions. It is the level or extent of these Engineering Changes that are critical in determining the *Lead Time* and *Labor cost* to complete the design work. If the level of

EC is low, then the design work finishes sooner. The reverse is true if the level of EC is high. To determine the number of ECs, we refer to Figure 3.7 from which

$$\begin{gathered}\textit{Numb of Engineering Changes (EC)} = \\ \textit{Cum Design Work Done} - \textit{Numb of Design Work Completed}\end{gathered} \qquad 3.23$$

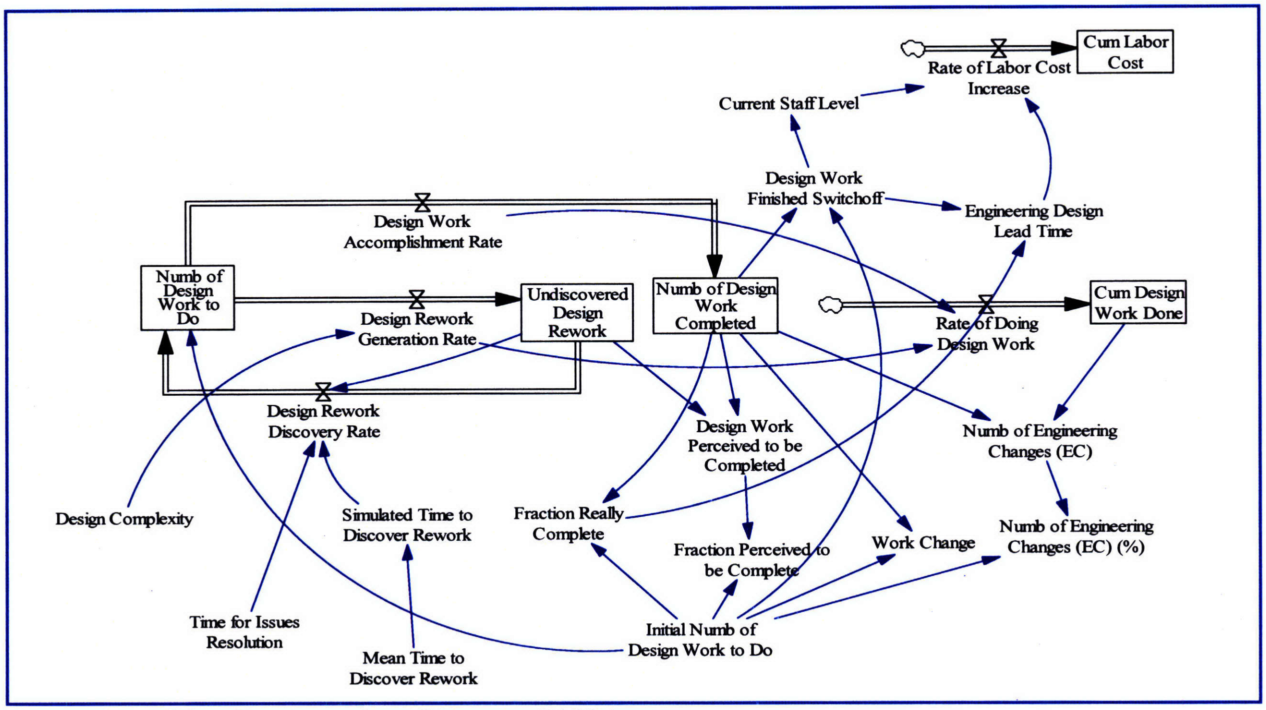


Figure 3.7: The Engineering Change (EC) Loops

$$\textit{Cum Design Work Done} = \int_0^T (\textit{Rate of Doing Design Work})dt \qquad 3.24$$

$$\begin{gathered}\textit{Rate of Doing Design Work} = \\ \textit{Design Rework Generation Rate} + \textit{Design Work Accomplishment Rate}\end{gathered} \qquad 3.25$$

The *Engineering Design Lead Time*, is the elapsed time when the ratio

$$\textit{Fraction Really Complete} = \frac{\textit{Numb of Design Work Completed}}{\textit{Initial Numb of Design Work to Do}} = 1$$

In this work, the ratio is set to .99 or 99% complete.

The *Labor cost* is given by

$$\textit{Cum Labor Cost} = \int_0^T (\textit{Rate of Labor Cost Increase})dt \qquad 3.26$$

$$Rate\ of\ Labor\ Cost\ Increase = Current\ Staff\ Level * Engineering\ Design\ Lead\ Time \quad 3.27$$

Figure 2.8 shows the complete model, where the model documentation is given in the Appendix

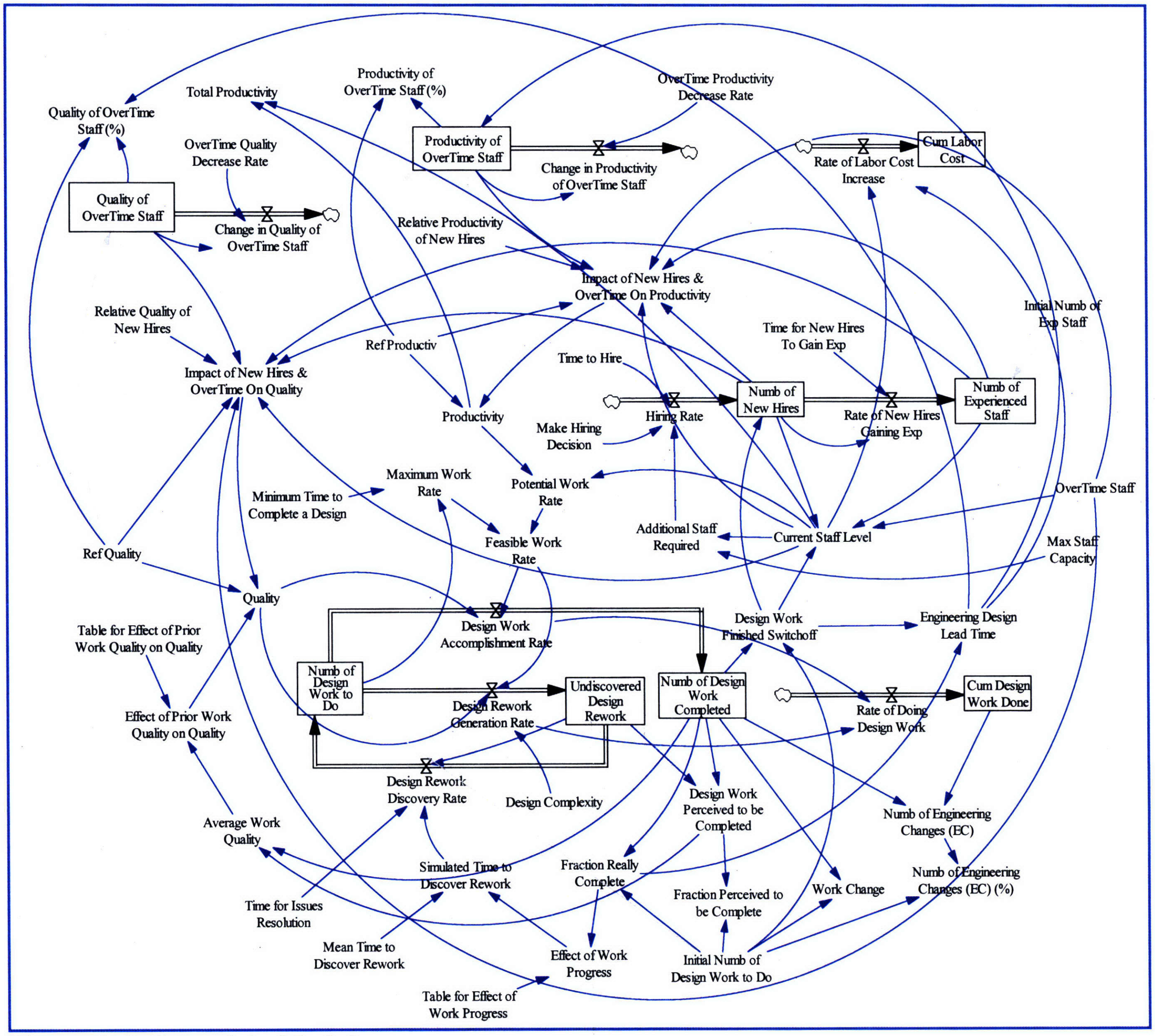


Figure 2.8: Complete Model

4. Simulations with Model – Sensitivity Analysis

4.1. Model Calibration

Before using the model to simulate the dynamics of various design scenarios, we first calibrate it with data from a real case. The real case used in the calibration had 474 Initial Design with *Engineering-Design-Lead-Time* of 18 months (or 360 days = 18 months x 20 days/month), and a *Cumulative-Design-Work-Done* of 1,100 Designs - which includes 474 Initial Designs + Design Changes or Revisions). Table 4.1 shows the settings of the model parameters or variables. We call this the Baseline Case in which the *Ref-Quality* (i. e. the percentage of the design work conforming to specification at each design iteration or quality check) is 52%.

Table 4.1

No	Variable Name	Baseline Values
1	*Ref-Quality*	52%
2	*Ref-Productivity*	0.01 Designs/Person-Day
3	*Design-Complexity*	1
4	*Initial-Numb-of-Design-Work-to-Do*	474 Designs
5	*Mean-Time-to-Discover-Rework*	4 Days
6	*Time-for-Issues-Resolution*	1 Days
7	*Minimum-Time-to-Perform-a-Design*	20 Days
8	*Relative-Quality-of-New-Hires*	26% (=50% of 52%)
9	*Relative Productivity-of-New-Hires*	0.005Designs/Person-Day (=50% of 0.01)
10	*Max-Staff-Capacity*	400
11	*Numb-of-Experienced-Staff*	200 persons
12	*Over-Time-Staff*	100 persons
13	*Over-Time-Quality-Decrease-Rate*	1/1000 per Day
14	*Over-Time-Productivity-Decrease-Rate*	1/1000 per Day
15	*Hiring-Rate*	10 persons/month
16	*Time-for-New-Hires-To-Gain-Experience*	90 Days

Figure 4.1 shows the result of the simulation which is the S-Curve of the Baseline Case. *The-Number-of-Design-Work-to-Do* starts with the *Initial-Numb-of-Design-Work-to-Do* value of 474 Designs and finishes in about 360 days.

Figure 4.2 shows S-Curve of the growth of the *Numb-of-Design-Work-Completed* which increases from its initial value of zero to 474 - as *The-Number-of-Design-Work-to-Do* decreases from 474 to zero.

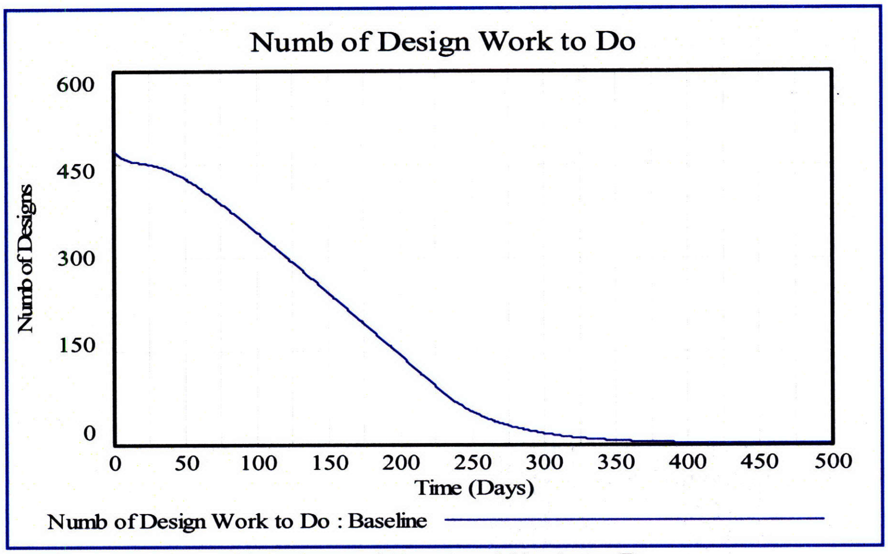


Figure 4.1: The Number of Design Work to Do

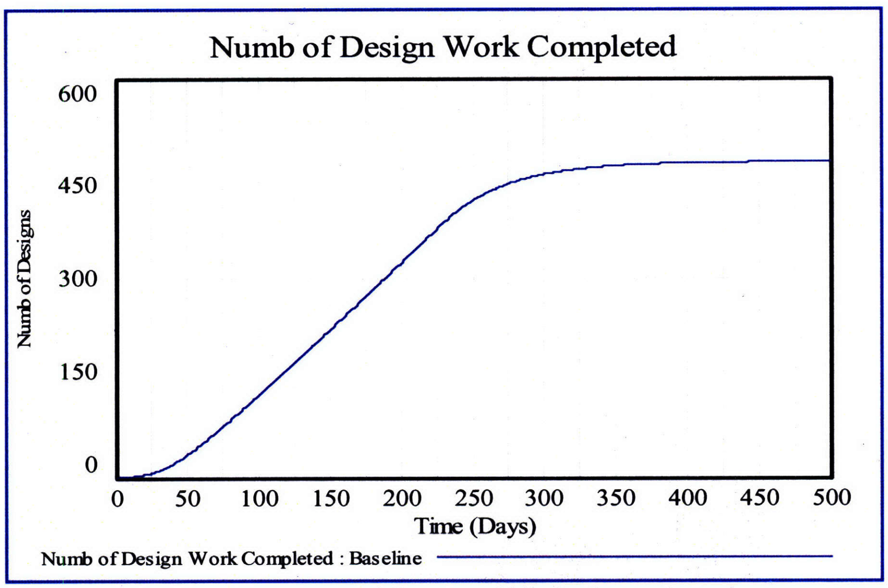


Figure 4.2: The Number of Design Work Completed

Figure 4.3 shows how the *Cumulative-Design-Work-Done* increases from its initial value of zero to 1,097 (which includes the original initial designs + the engineering changes)- as *The-Number-of-Design-Work-to-Do* decreases to zero from its initial value of 474. The *Cumulative-Design-Work-Done* > *Initial-Numb-of-Design-Work-to-Do* as a result of several factors, including the Baseline *Quality* of 52% and *Mean-Tim- to-Discover-Rework, Time-for-Issues-Resolution,* etc.

Figure 4.4 shows the *Numb-of-Engineering-Changes (EC)* generated by the Baseline case is 623 (=1,097 – 474). Figure 4.5 shows that the *EC* generated by the Baseline case is about 132% (=623/474). We therefore say that the Rework generated in the Baseline case is 132%.

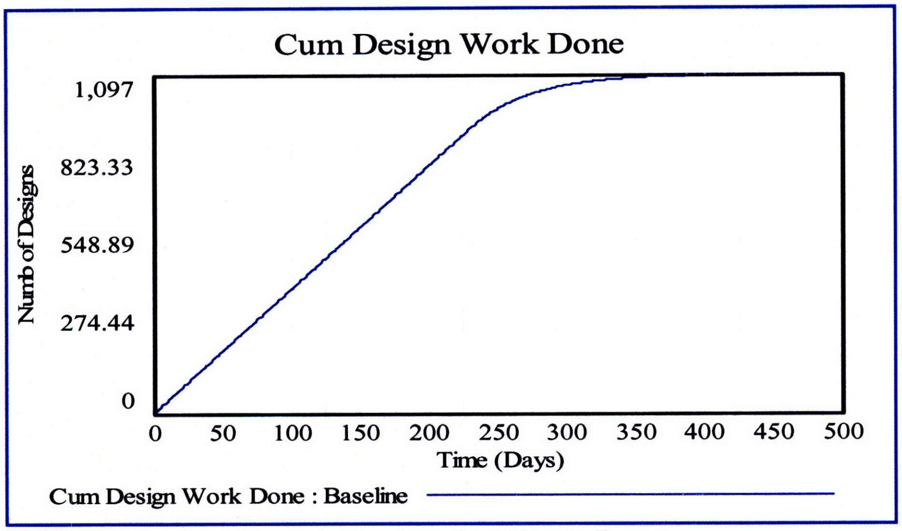


Figure 4.3: The Cumulative Design Work Done

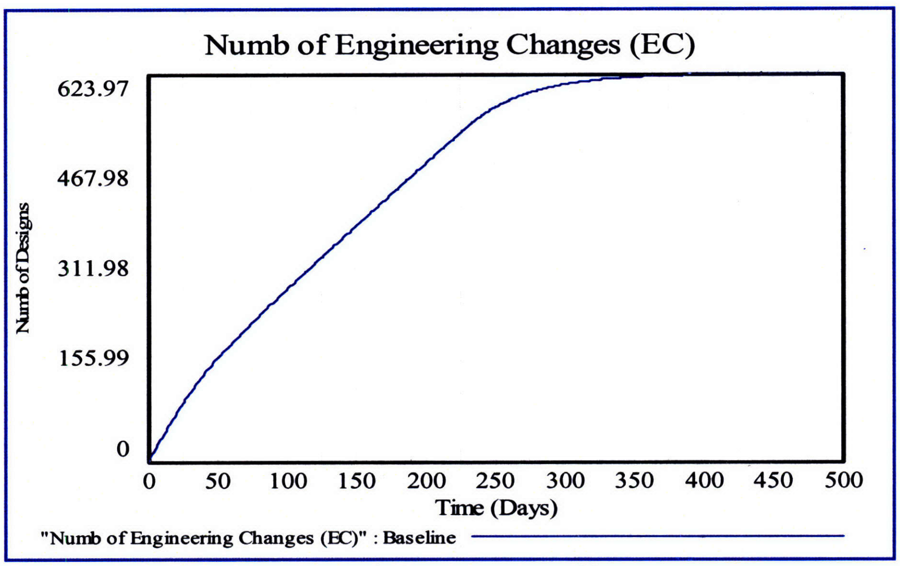


Figure 4.4: The Number of Engineering Changes

For an appreciation of the impact of *Quality* on the generation of rework, we compare the Baseline case with 52% *Quality* with the Perfect Quality case with 100% *Quality* in figure 4.6. Note that if work were to be accomplished with perfect Quality, the *Engineering-Design-Lead-Time* would be only about 150 Days, that is 210 (= 360 – 150) days earlier than the Baseline case

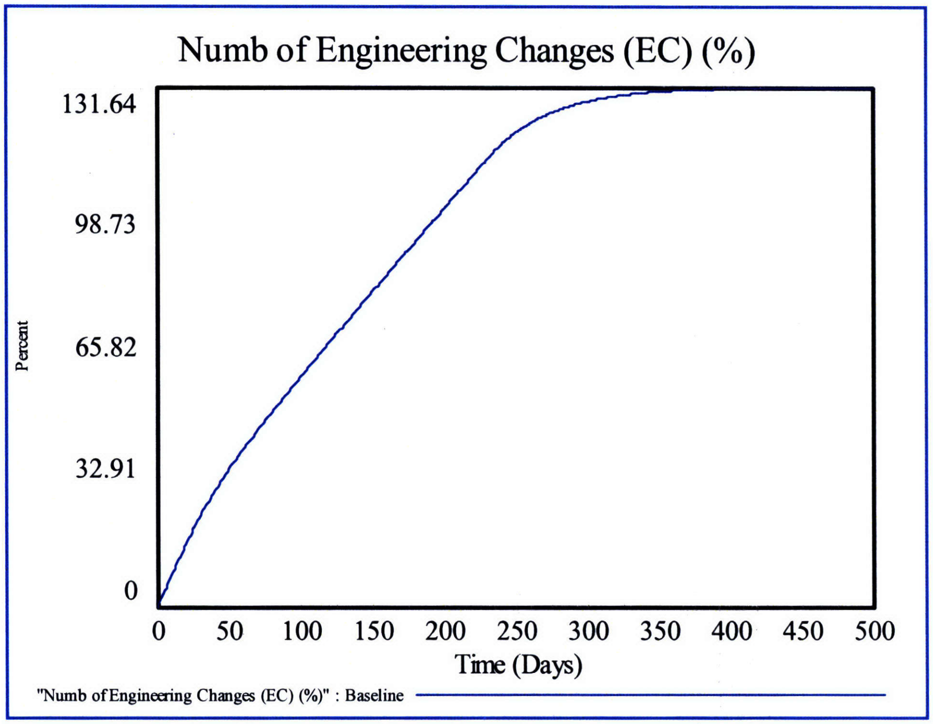


Figure 4.5: The Number of Engineering Changes (%)

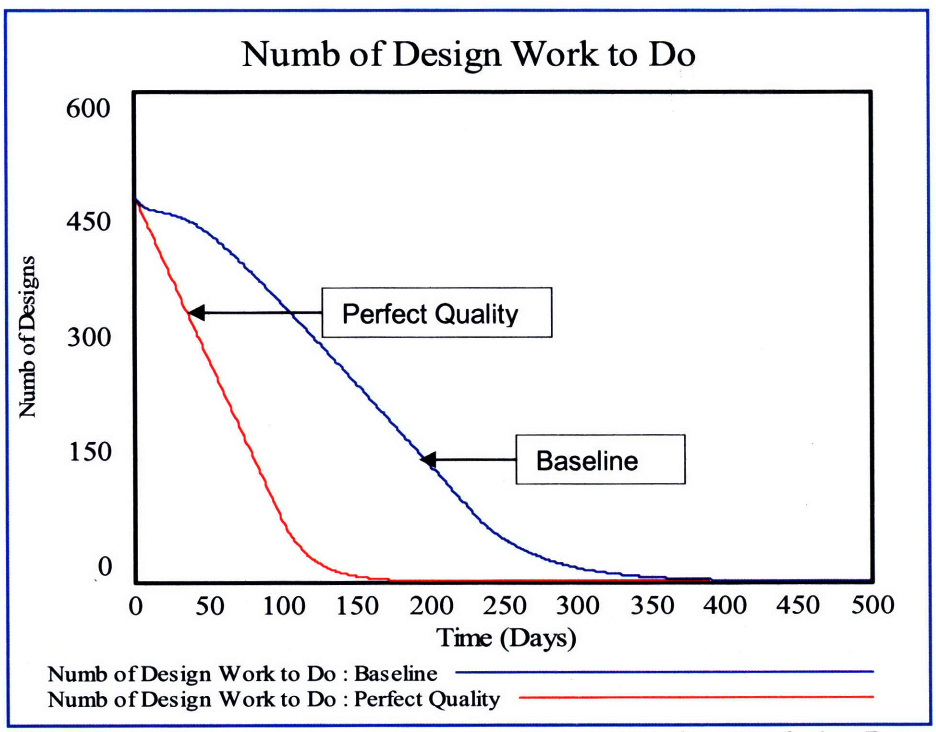


Figure 4.6: A comparison of the Perfect 100% Quality & the Baseline case (52%)

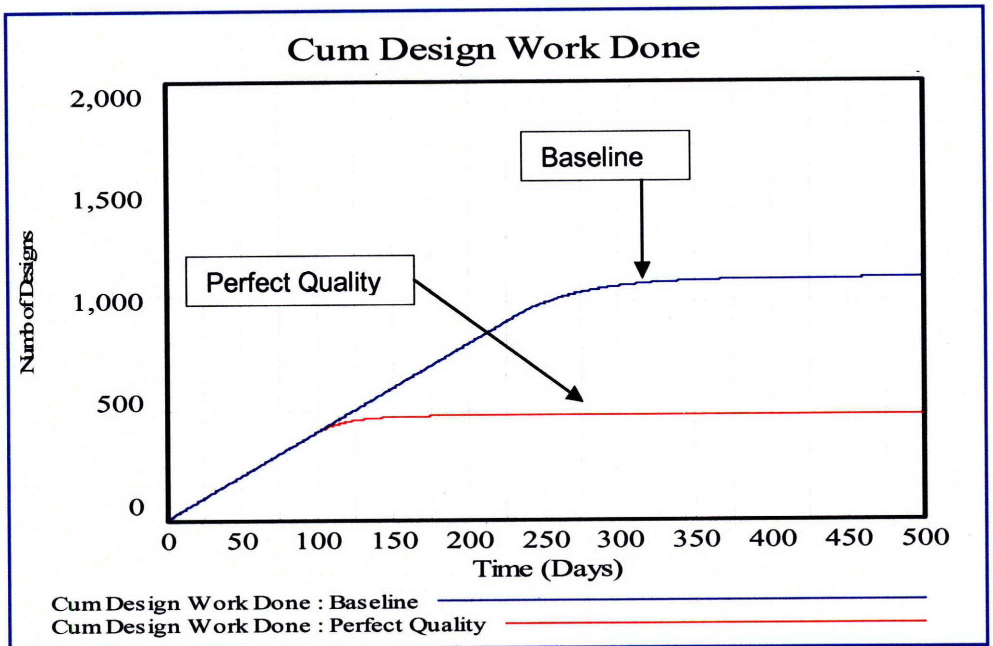


Figure 4.7: A comparison of the Perfect 100% Quality & the Baseline case (52%)

Figure 4.7 shows a comparison of the *Cumulative-Design-Work-Done* for the Baseline and the Perfect Quality cases. We see that in the Perfect Quality case, the *Cumulative-Design-Work-Done* is same as the *Initial-Numb-of-Design-Work-to-Do.* In the Baseline case, the *Cumulative-Design-Work-Done* exceeds the *Initial-Numb-of-Design-Work-to-Do* by 623 (=1,097 – 474) which is the amount of EC or Rework generated.

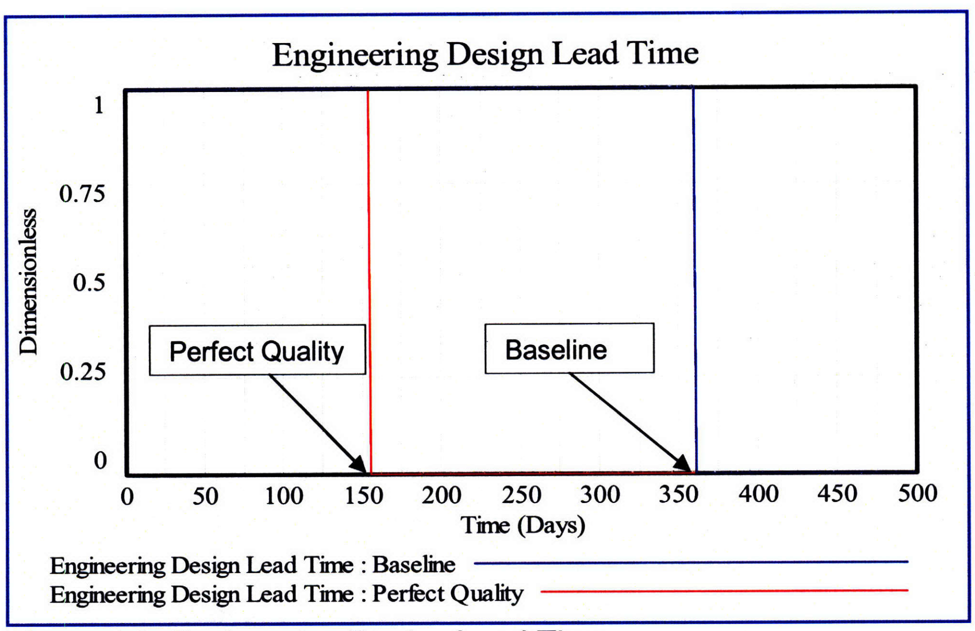


Figure 4.8: Engineering Design Lead Time

Figure 4.8 shows a comparison of the *Engineering-Design-Lead-Time* for the Baseline and Perfect Quality cases. We see that the Perfect Quality (100%) case finishes in 155 days, compared to 360 for the 52% Quality Baseline case.

4.2. Impact of *Quality* on Rework Generation

In this section we employ the model to study the impact of *Quality* on Rework generation – and the corresponding impacts on *Lead Time* and *Labor cost* - by simulating the model for different values (40%, 52% - Baseline, 60%) of *Quality*. In Table 4.2 the *Ref-Quality* is the variable that is changing values as shown.

Table 4.2: Sensitivity Analysis - Simulating the impact of Quality

No	Variable name	Baseline Values
1	***Ref-Quality***	**40%, 52% - Baseline, 60%**
2	*Ref-Productivity*	0.01 Designs/Person-Day
3	*Design-Complexity*	1
4	*Initial-Numb-of-Design-Work-to-Do*	474 Designs
5	*Mean-Time-to-Discover-Rework*	4 Days
6	*Time-for-Issues-Resolution*	1 Days
7	*Minimum-Time-to-Perform-a-Design*	20 Days
8	*Relative-Quality-of-New-Hires*	26% (=50% of 52%)
9	*Relative Productivity-of-New-Hires*	0.005Designs/Person-Day (=50% of 0.01)
10	*Max-Staff-Capacity*	400
11	*Numb-of-Experienced-Staff*	200 persons
12	*Over-Time-Staff*	100 persons
13	*Over-Time-Quality-Decrease-Rate*	1/1000 per Day
14	*Over-Time-Productivity-Decrease-Rate*	1/1000 per Day
15	*Hiring-Rate*	10 persons/month
16	*Time-for-New-Hires-To-Gain-Experience*	90 Days

Figure 4.9 shows the impact of *Quality* on *Engineering-Design-Lead-Time.* A 40% Quality, gives the longest *Lead Time* of 477 Days, followed by the Baseline case (52% *Quality*), with *Engineering-Design-Lead-Time* of 360 Days and finally, the 60% Quality case with the shortest *Lead Time* of 312 Days.

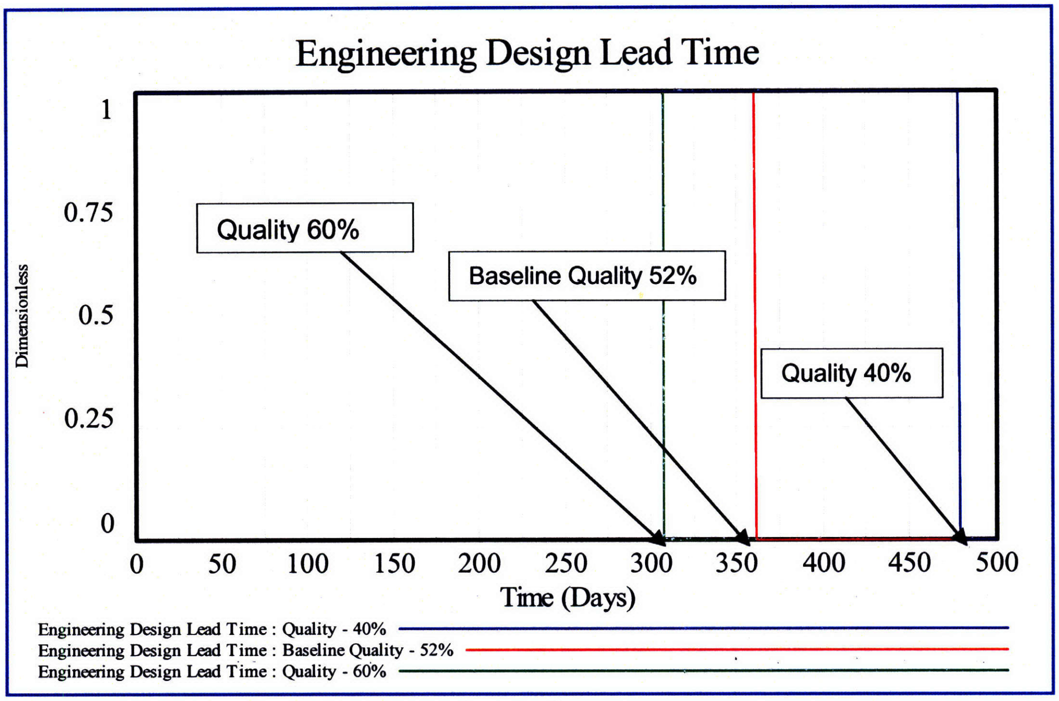


Figure 4.9: Impact of Quality on Lead Time

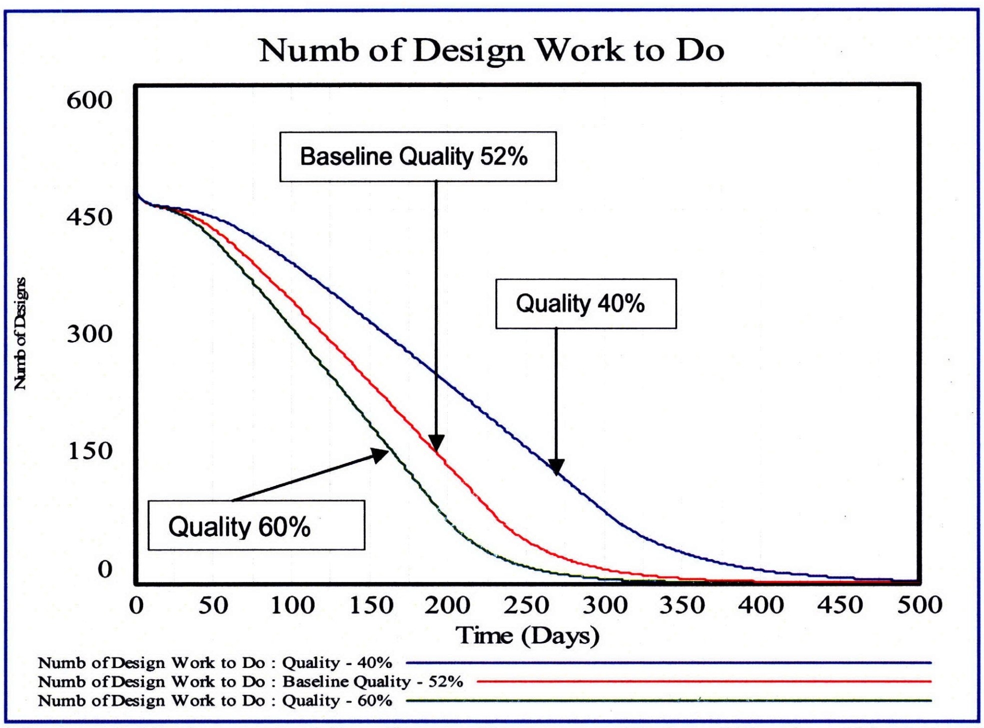


Figure 4.10: Impact of Quality on Decrease Rate of Design Work to Do

Figure 4.10 shows the S-curves for the decrease rates of the *Numb-of-Design-Work-to-Do* for the three different *Ref-Quality* values as work progresses. Note that as Quality decreases, the rate of work accomplishment decreases because of increase in Rework generation. Thus, we see that the decrease rates of the *Numb-of-Design-Work-to-Do* is highest for 60% Quality and lowest for 40% Quality.

Figure 4.11 shows the S-curves for the increase rates of the *Numb-of-Design-Work-Completed* for the three different *Ref-Quality* values as work progresses. Here we see that the higher the *Quality*, the higher the rate of increase of *Numb-of-Design-Work-Completed* – since higher *Quality* means that less rework is being generated. We thus observe that the S-curves for the 60% *Quality* case increases fastest, while the 40% Quality case increases at the lowest rate.

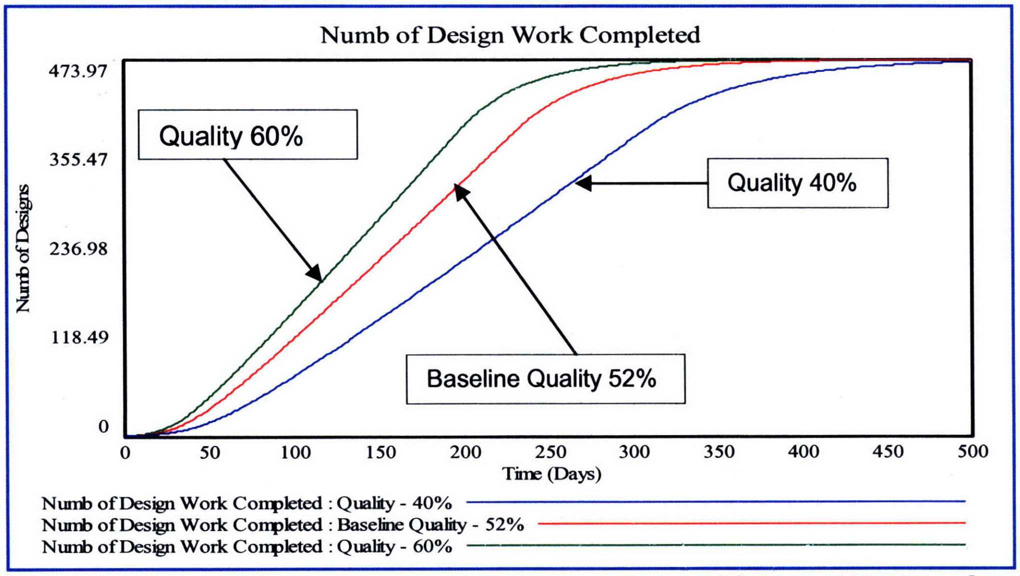


Figure 4.11: Impact of Quality on Increase Rate of Design Work to Completed

Figure 4.12 shows the *Quality* curves for the three cases. The *Quality* in all cases dip initially before recovering to attain their maximum values of 40%, 52% and 60%. The reason for the dip is due to the Effect of Prior Quality on Quality which get worse as *Quality* decreases. Consequently, the 40% curve dips more than the 52% curve, and the 52% curve dips more than the 60% curve. Note that the of 60% Quality curve reaches its maximum faster than the 52% Baseline case, while the 40% Quality curve is the slowest in attaining its maximum.

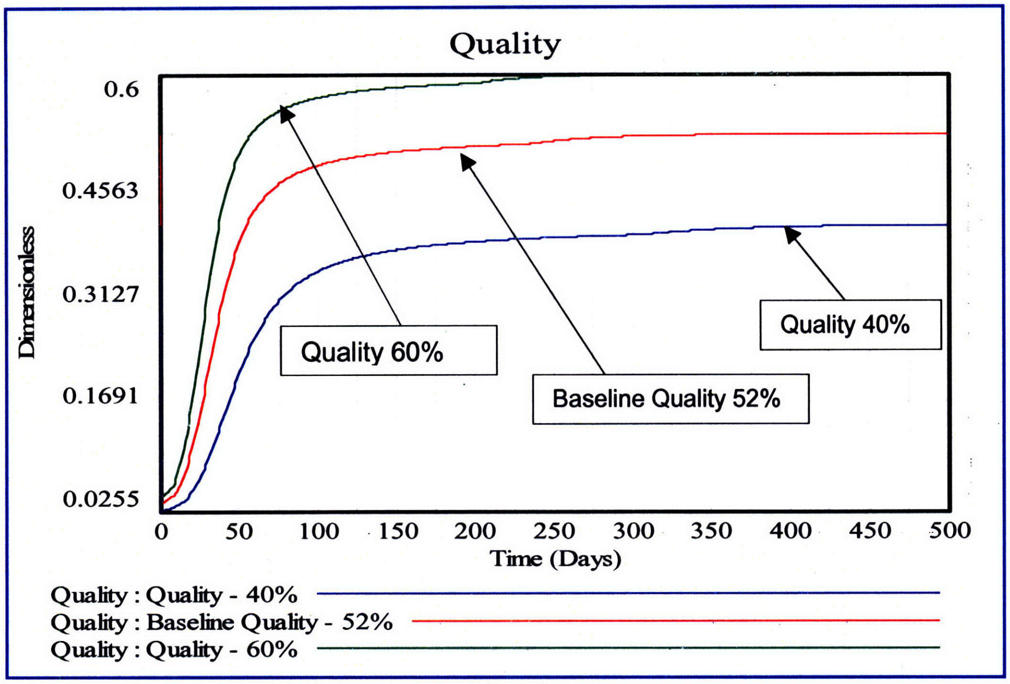


Figure 4.12: Impact of Quality on Quality

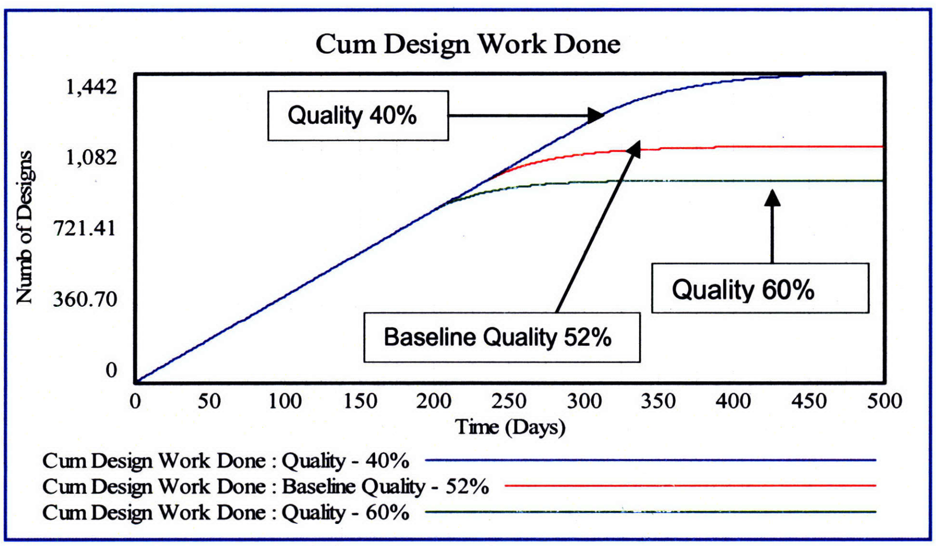


Figure 4.13: Impact of Quality on Cumulative Design Work Done

Figure 4.13 shows that 40% *Quality* results in about 1,442 cumulative Designs from the initial 474 Designs, while 52% *Quality* produces 1,093 and 60% *Quality* results in 940.cumulative Designs.

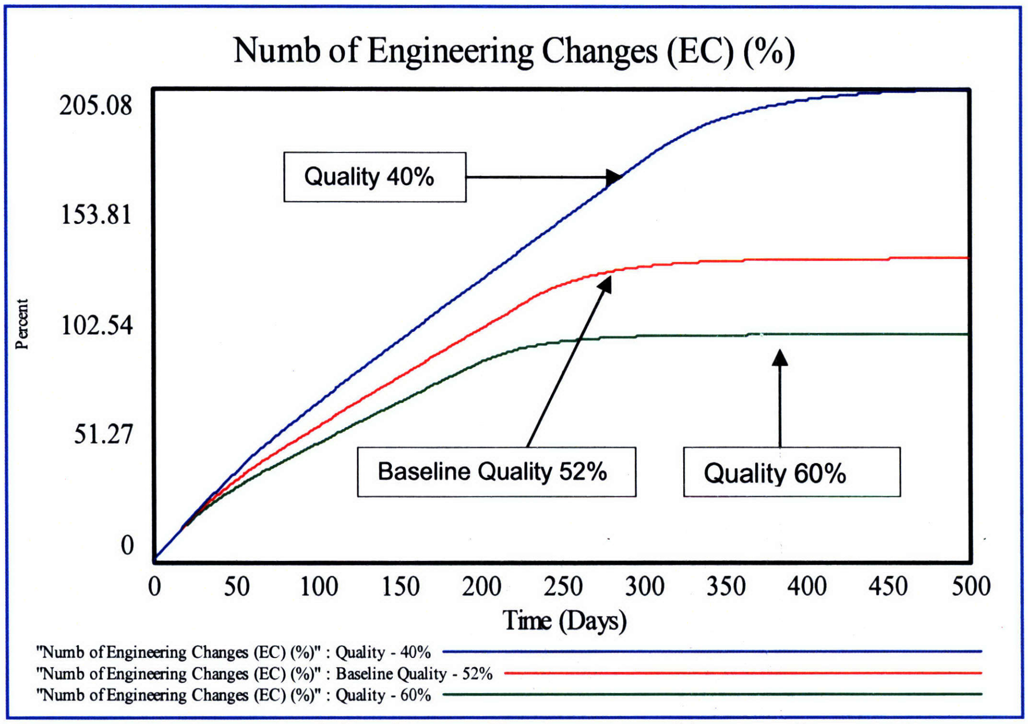


Figure 4.14: Impact of Quality on Engineering Change Generation

Figure 4.14 shows the percentage of EC generated at the three Quality levels. We see that 40% Quality generates the highest EC of 190%, followed by 52% Quality Baseline case with 132%, while 60% Quality generates the lowest EC at 84%

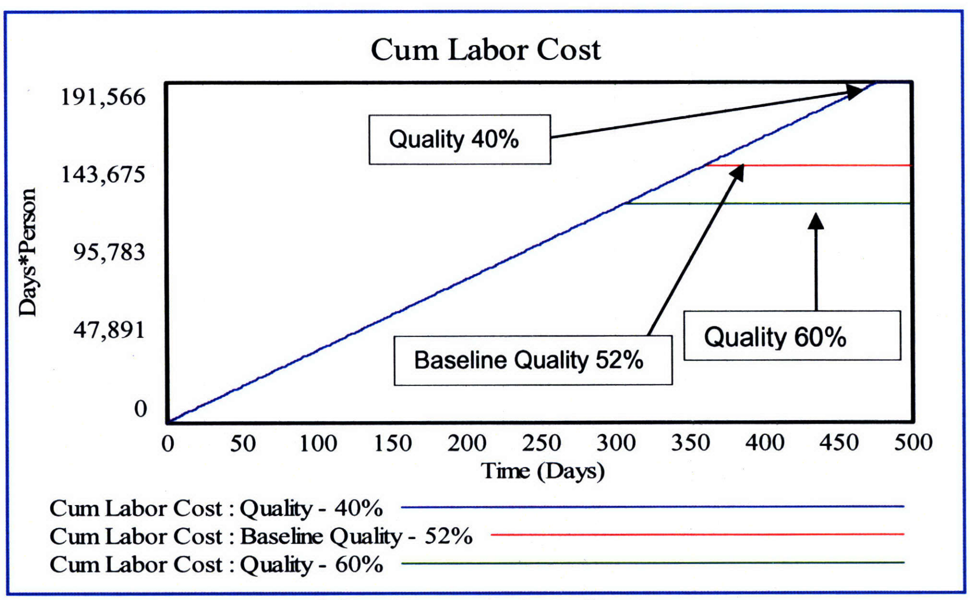


Figure 4.15: Impact of Quality on Labor Costs

Figure 4.15 shows the corresponding labor costs at the three Quality levels. 40% Quality results in the highest Labor cost of $183,200 followed by 52% Quality Baseline case with $144,158 while 60% Quality results in the lowest Labor Cost of $115,600.

4.3. Impact of *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on EC (Engineering Change) Generation

In this section we employ the model to study the impact of *Mean Time to Discover Rework* & *Time for Issues Resolution* on EC Generation by simulating the model for different values of *Mean Time to Discover Rework* + *Time for Issues Resolution* as shown in Table 4.3. Note that *Mean Time to Discover Rework* and *Time for Issues Resolution* have been lumped together for convenience.

Table 4.3: Sensitivity Analysis – Impact of *Mean Time to Discover Rework* and *Time for Issues Resolution*

No	Variable name	Baseline Values
1	*Ref Quality*	52% - Baseline
2	*Ref-Productivity*	0.01 Designs/Person-Day
3	*Design-Complexity*	1
4	*Initial-Numb-of-Design-Work-to-Do*	474 Designs
5	***Mean-Time-to-Discover-Rework***	**5, 10, 20 Days**
6	***Time-for-Issues-Resolution***	
7	*Minimum-Time-to-Perform-a-Design*	20 Days
8	*Relative-Quality-of-New-Hires*	0.5
9	*Relative Productivity-of-New-Hires*	0.5
10	*Max-Staff-Capacity*	400
11	*Numb-of-Experienced-Staff*	200 persons
12	*Over-Time-Staff*	100 persons
13	*Over-Time-Quality-Decrease-Rate*	1/1000 per Day
14	*Over-Time-Productivity-Decrease-Rate*	1/1000 per Day
15	*Hiring-Rate*	10 persons/month
16	*Time-for-New-Hires-To-Gain-Experience*	90 Days

Figure 4.16 shows the *Numb-of-Design-Work-to-Do* for *Mean-Time-to-Discover Rework* + *Time-for-Issues-Resolution* of 5, 10 and 20 Days. A look at the curve for the 5 Days delay (Blue line) shows a section where the slope or gradient is less steep near the top indicated by the arrow which shows the delay in rework discovery. The earlier the reworks are discovered, the closer to the top the delay is, and the earlier the defects get fixed which has the effect of enabling the design work to finish earlier. Notice that as the *Mean-Time-to-Discover Rework* + *Time-for-Issues-Resolution* increase to 10 days (Red line), the delay shows up later in the design process and last longer compared to the case when *Mean-Time-to-Discover Rework* + *Time-for-Issues-Resolution* was 5 days.

Similarly, as the *Mean-Time-to-Discover Rework* + *Time-for-Issues-Resolution* increase from 10 to 20 days (Green line), the delay shows up even later in the design process and last even longer compared to the case when *Mean-Time-to-Discover Rework* + *Time-for-Issues-Resolution* was 10 days. In general, as *Mean-Time-to-Discover Rework* + *Time-for-Issues-Resolution* increase, this causes the delay to show up later and later in the design process and last longer, consequently causing the work to finish later and later.

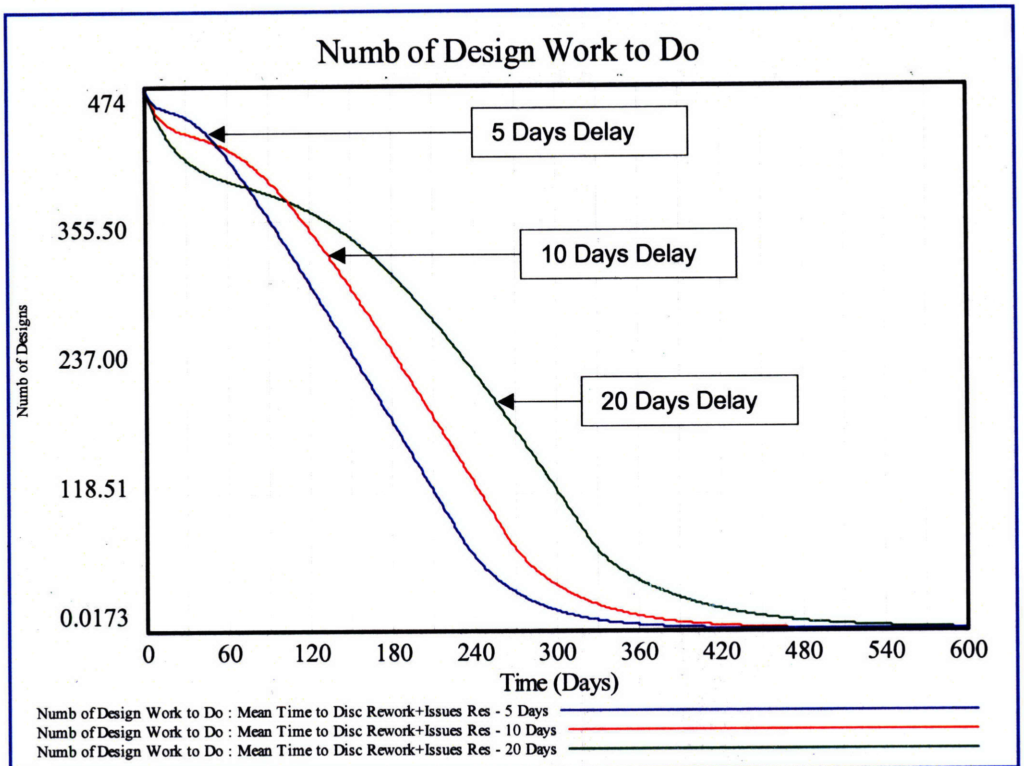


Figure 4.16: Impact of Time-to-Discover Rework & Time-for-Issues-Resolution on Number of Design Work to Do

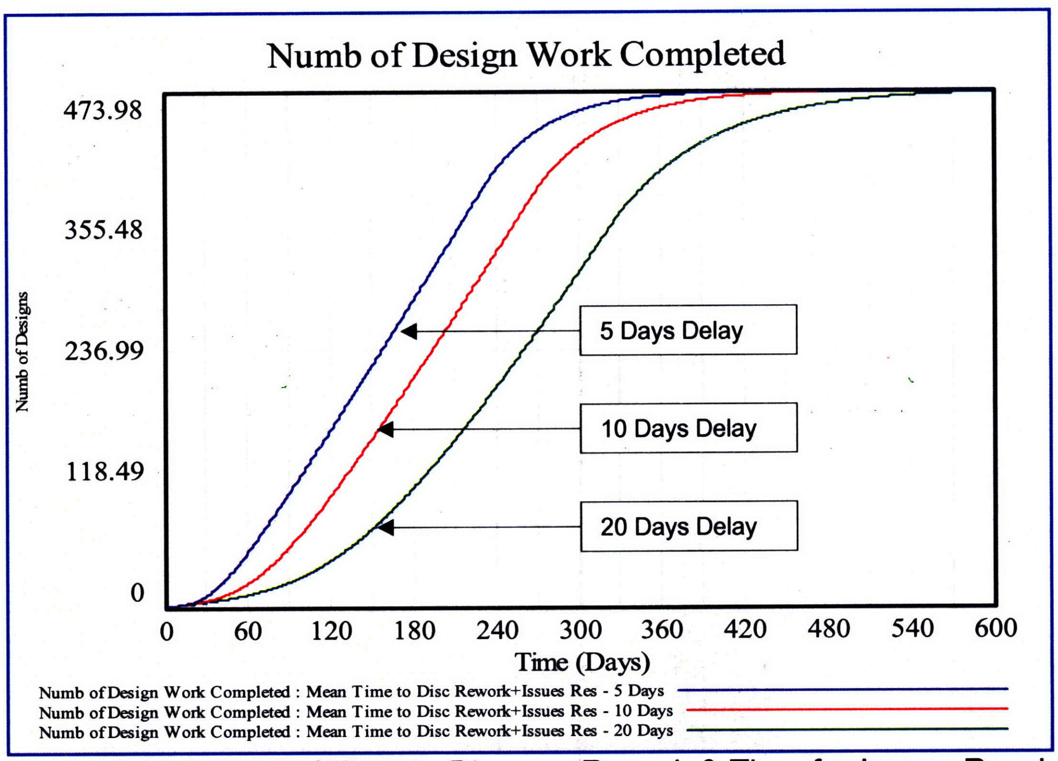


Figure 4.17: Impact of Time-to-Discover Rework & Time-for-Issues-Resolution on Number of Design Work Completed

Figure 4.17 shows the *Numb-of-Design-Work-Completed* for the three cases. Note that the case for *Mean-Time-to-Discover Rework + Time-for-Issues-Resolution* = 5 days (Blue line), finishes earliest, followed by the case with 10 days delay (Red line), and finally the case with 20 days delay (Green line).

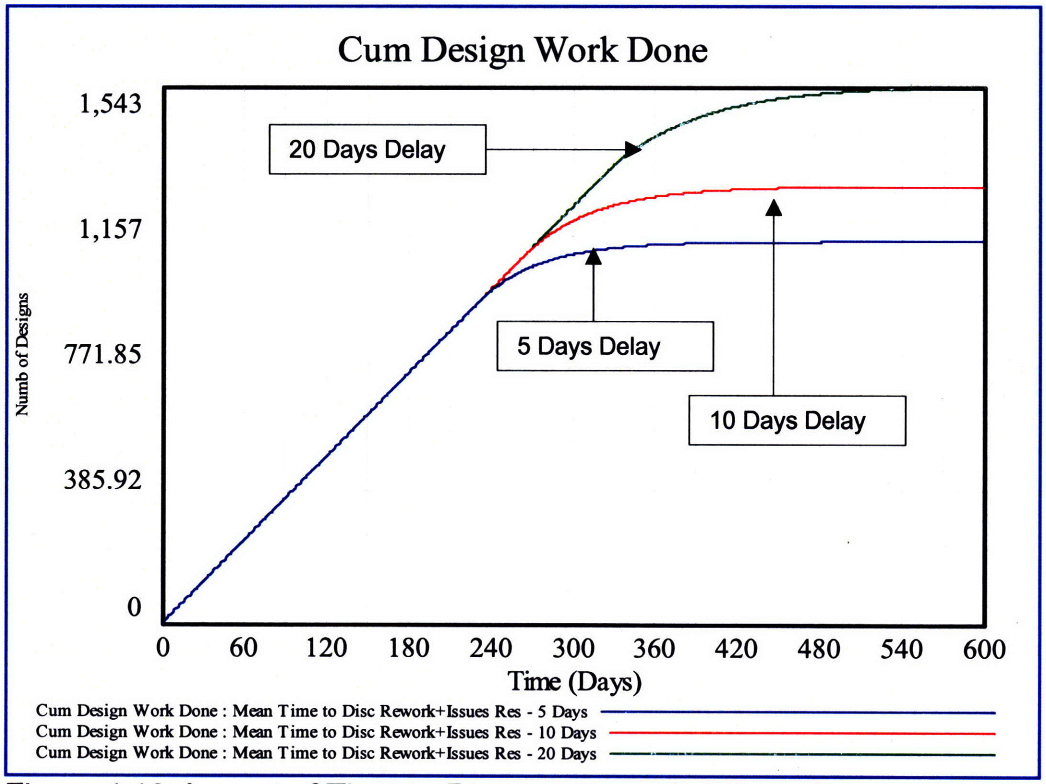


Figure 4.18: Impact of Time-to-Discover Rework & Time-for-Issues-Resolution on Cumulative Design Work Done

Figure 4.18 shows the *Cumulative-Work-Done* for the three cases. The case for *Mean-Time-to-Discover Rework + Time-for-Issues-Resolution* = 5 days (Blue line) results in the smallest cumulative work done (1,098), followed by the case with 10 days delay at 1,258 (Red line), and the case with 20 days delay (Green line) has the highest cumulative work done of 1,548.

Figure 4.19 shows the *Numb-of-Engineering-Changes (EC)* generated for the three cases. The case for *Mean-Time-to-Discover Rework + Time-for-Issues-Resolution* = 5 days (Blue line), generates 132% of EC, followed by the case with 10 days delay (Red line) with 165%, and finally the case with 20 days delay (Green line) with 226%.

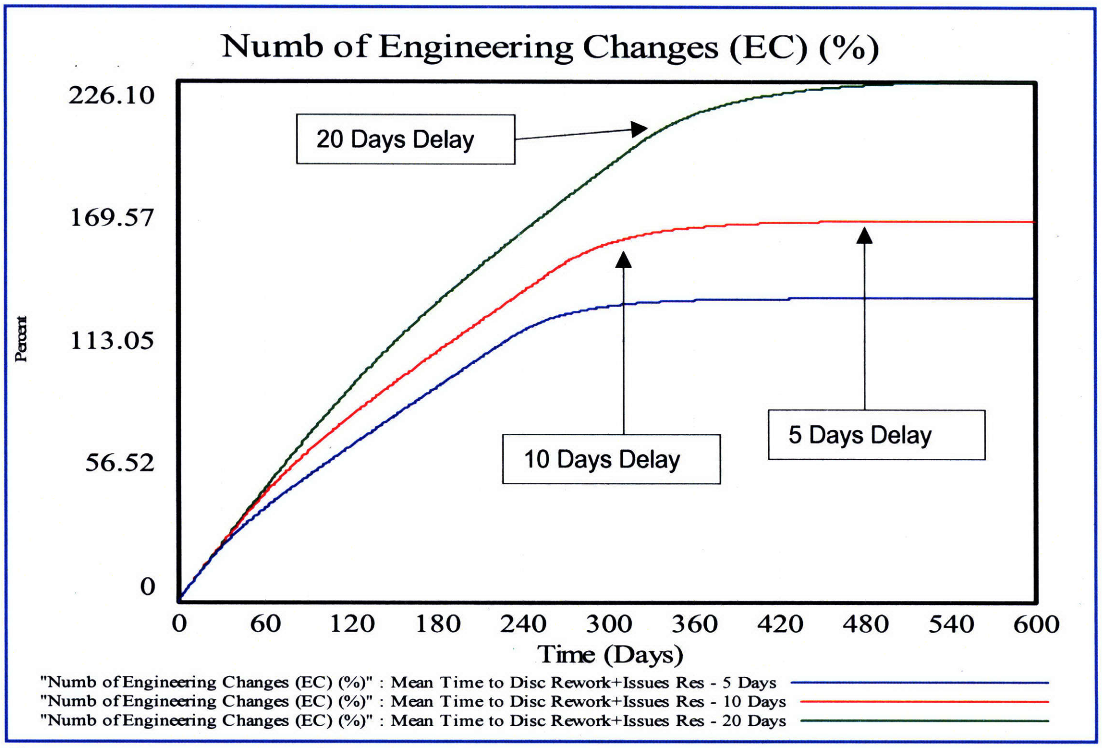


Figure 4.19: Impact of Time-to-Discover Rework & Time-for-Issues-Resolution on Engineering Change Generation

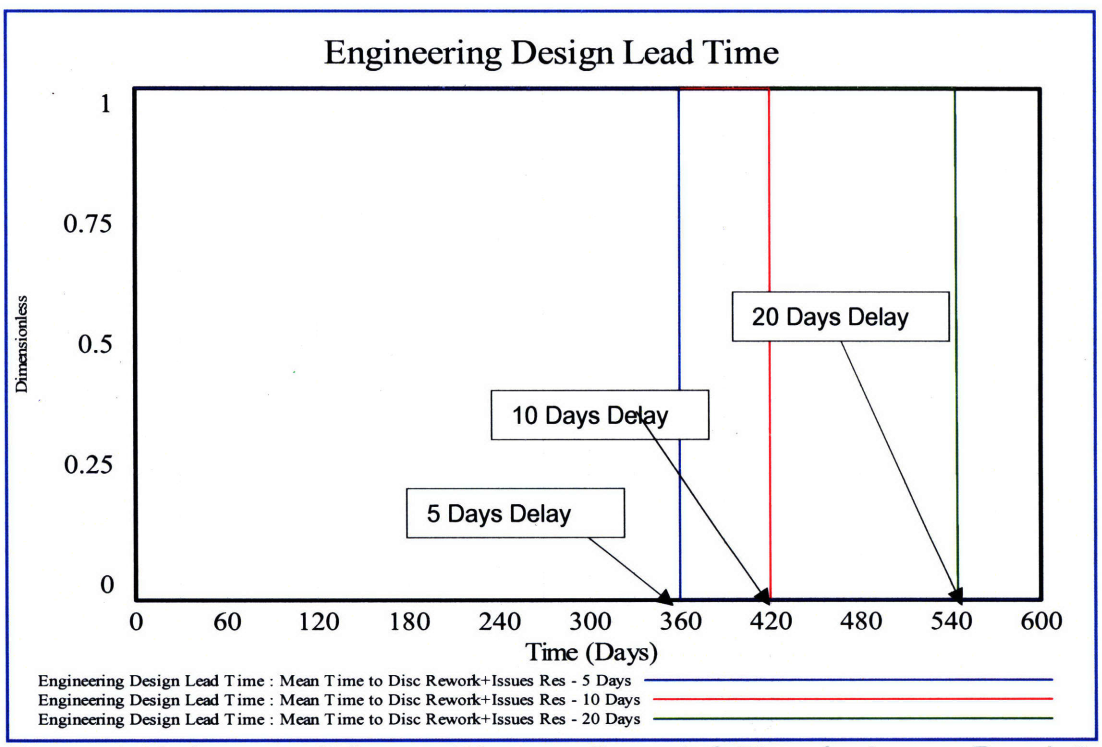


Figure 4.20: Impact of Time-to-Discover Rework & Time-for-Issues-Resolution on Lead Time

Figure 4.20 shows the *Engineering-Design-Lead-Time* for the three cases. The case for *Mean-Time-to-Discover Rework + Time-for-Issues-Resolution* = 5 days (Blue line), results in 360 Days, followed by the case with 10 days delay (Red line) with 421 Days and case with 20 days delay (Green line) with 545 Days

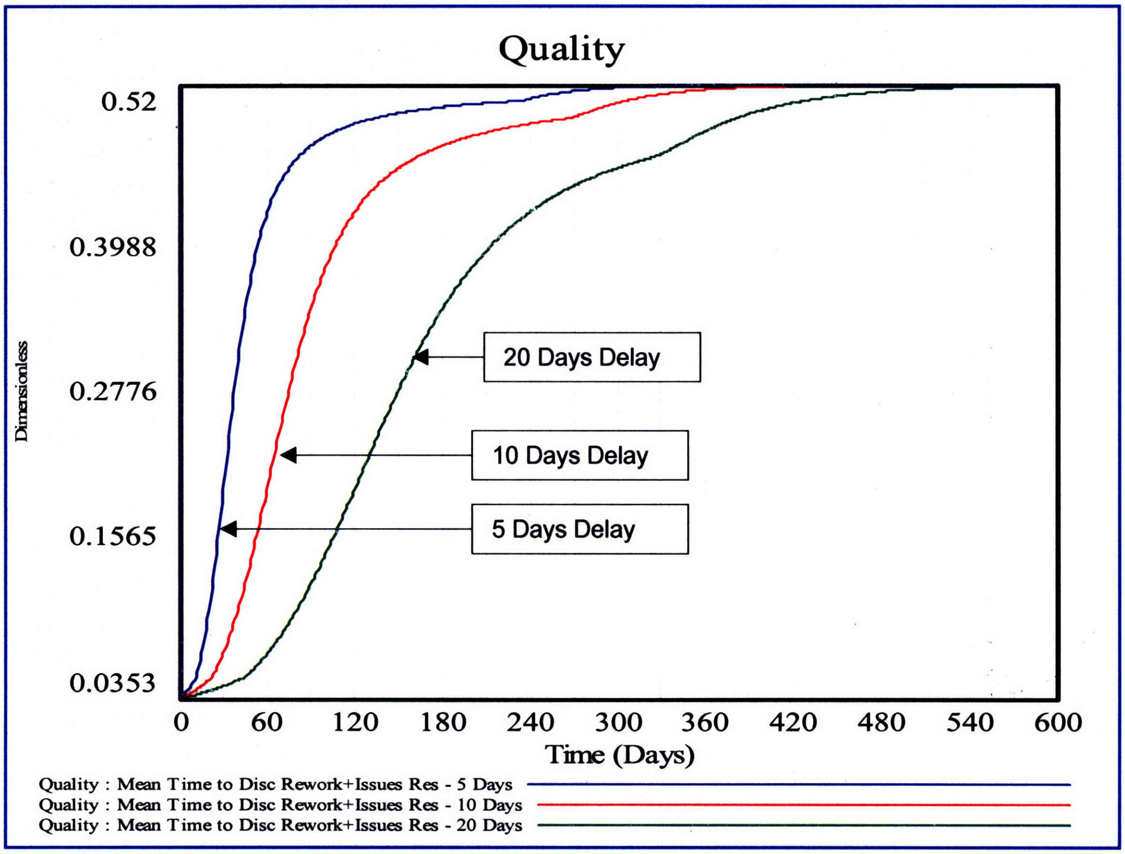


Figure 4.21: Impact of Time-to-Discover Rework & Time-for-Issues-Resolution on Quality

Figure 4.21 shows the impact of *Mean-Time-To-Discover-Rework + Time-for-Issues-Resolution* on *Quality* for the three cases. *Quality* is seen to be negatively impacted by the delay in Rework discovery. *Quality* is seen to decrease as the *Mean Time to Discover Rework + Time for Issues Resolution* increase from 5 days (Blue line) to 10 days delay (Red line) and to 20 days delay (Green line).

Figure 4.22 shows the impact of *Cumulative Labor Cost* for the three cases which is seen to be negatively impacted by the delay in rework discovery. *Cumulative Labor Cost* is seen to increase from $144,167 for *Mean Time to Discover Rework + Time for Issues Resolution* = 5 days (Blue line); to $168,167 for 10 days delay (Red line) and to $217,633 for 20 days delay (Green line).

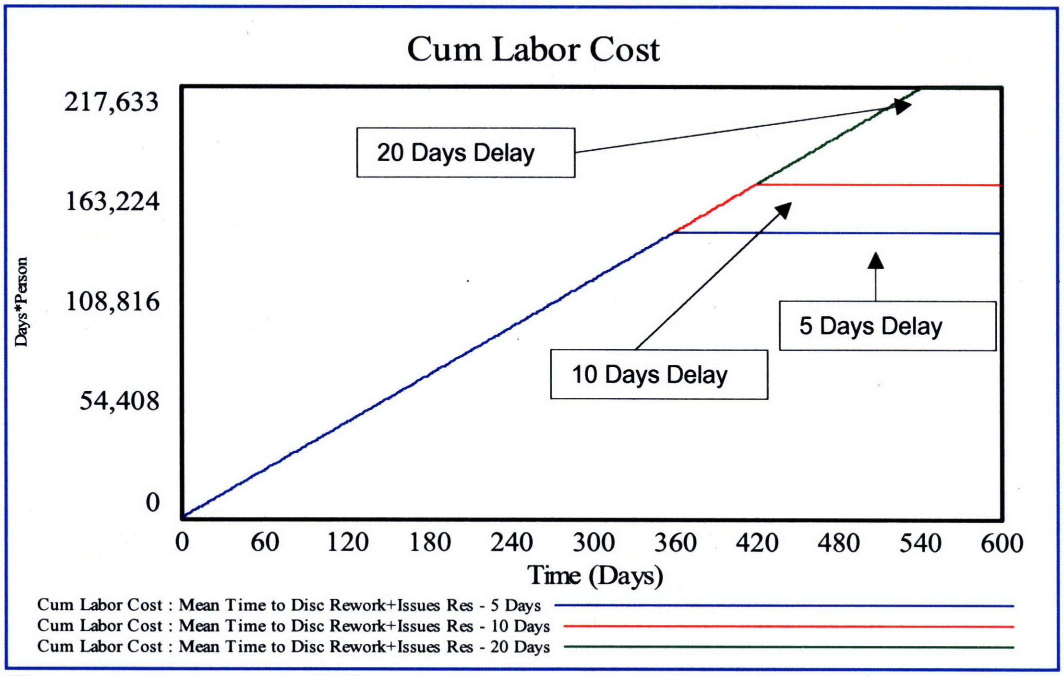


Figure 4.22: Impact of Time-to-Discover Rework & Time-for-Issues-Resolution on Labor Cost

4.4. Combined Impact of *Mean Time to Discover Rework* & *Time for Issues Resolution* & *Design Complexity* on EC (Engineering Change) Generation

In the last section we employed the model to study the impact of *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on Engineering Change generation by simulating the model for different values of *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution*. In this section we investigate the combined impact of *Design-Complexity* and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on the generation of Engineering Change.

Complexity is defined as a measure of how coupled the system or subsystem being designed is. A coupled system means that the design of a subsystem is constrained by other subsystem specifications or requirements. In other words, the design of the subsystems of a coupled system must take into consideration the design of other subsystems with which it is coupled. As a consequence of coupling, a change in the design of a subsystems that is part of a coupled system automatically triggers changes in all other subsystems with which it interacts. The *Design-Complexity* is thus a measure of the degree of coupling and the impact of a single Design Change on the whole system.

Figure 4.23 shows the *Design-Complexity* levels of the subsystems of a CH-53 Heavy Lift Replacement Helicopter, courtesy of Sikorsky Aircraft Company, Stratford, Connecticut. The *Design-Complexity* level of each subsystem is indicated by a number 1, 2, or 3 in parenthesis. The Airframe has the lowest *Design-Complexity* and is used as the reference Baseline.

Table 4.4: Sensitivity Analysis - Impact of *Design-Complexity & Time-to-Discover-Rework & Time-for-Issues-Resolution*

No	Variable Name	Baseline Values
1	*Ref-Quality*	52% - Baseline
2	*Ref-Productivity*	0.01 Designs/Person-Day
3	***Design-Complexity***	**1, 2**
4	*Initial-Numb-of-Design-Work-to-Do*	474 Designs
5	***Mean-Time to-Discover-Rework +***	**5, 20, Days**
6	***Time-for-Issues-Resolution***	
7	*Minimum-Time-to-Perform-a-Design*	20 Days
8	*Relative-Quality-of-New-Hires*	0.5
9	*Relative Productivity-of-New-Hires*	0.5
10	*Max-Staff-Capacity*	400
11	*Numb-of-Experienced-Staff*	200 persons
12	*Over-Time-Staff*	100 persons
13	*Over-Time-Quality-Decrease-Rate*	1/1000 per Day
14	*Over-Time-Productivity-Decrease-Rate*	1/1000 per Day
15	*Hiring-Rate*	10 persons/month
16	*Time-for-New-Hires-To-Gain-Experience*	90 Days

Two levels - 1, 2 of *Design-Complexity*, and two values – 5, 20 Days of the *Mean-Time-to-Discover-Rework & Time-for-Issues-Resolution* as shown in Table 4.4 are used in the analysis.

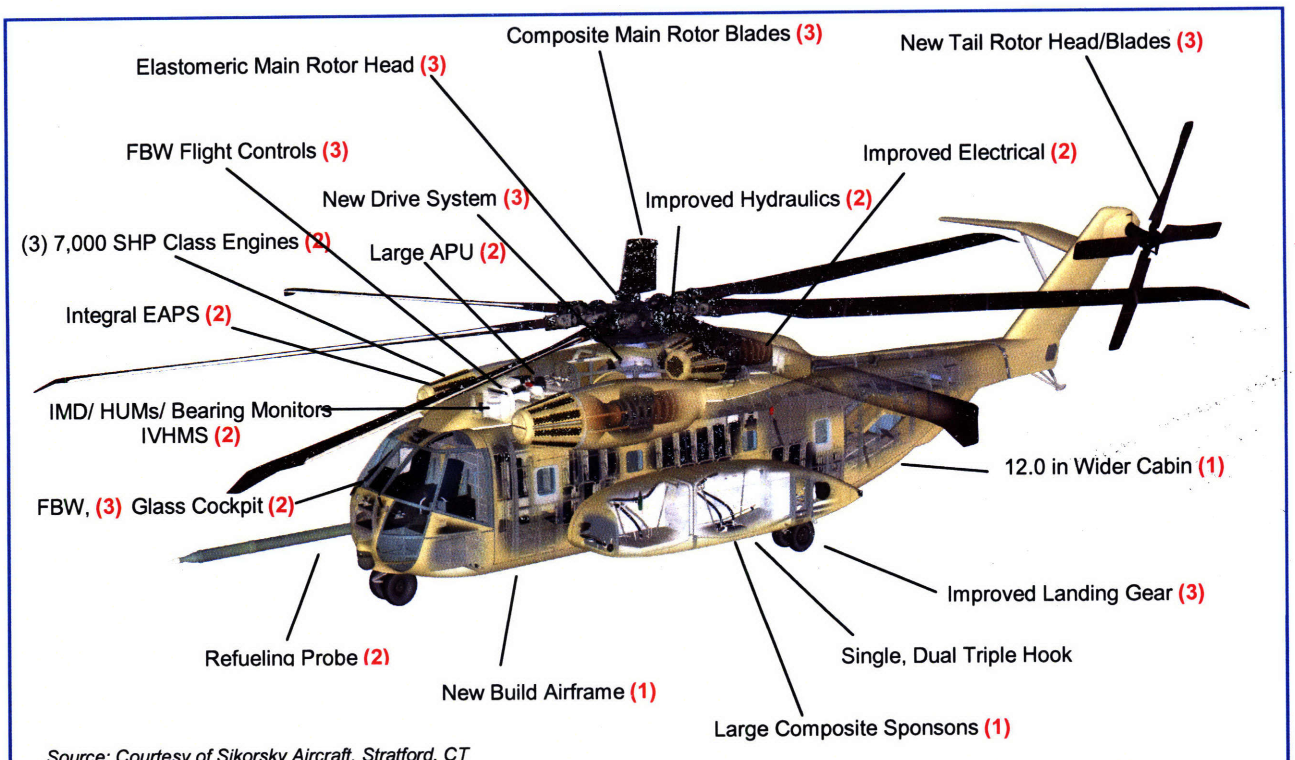


Figure 4.23: Sikorsky CH-53E Helicopter - Subsystem Design Complexity Levels

The subsystems complexity is as shown below in Table 4.5. The more complex or coupled the system is, the more the number of design changes that will be triggered by a single design change that is made.

Table 4.5: Design Complexity Levels for Aircraft Subsystems

Complexity Level 1	Complexity Level 2	Complexity Level 3
New Build Airframe	7,000 SHP Class Engines	New Drive System
Large Composite Sponsons	Large APU	FBW Flight Controls
12.0 in Wider Cabin	Integral EAPS	Elastomeric Main Rotor Head
	IMD/ HUMs/ Bearing Monitors IVHMS	Composite Main Rotor Blades
	Glass Cockpit	New Tail Rotor Head/Blades
	Refueling Probe	Improved Landing Gear
	Improved Electrical	Single, Dual Triple Hook
		FBW

Table 4.6: Simulation Plan for *Design-Complexity* & *Time-to-Discover-Rework* & *Time-for-Issues-Resolution*

Simulation No	Simulation Plan	Values
1	*Design Complexity* *Mean Time to Discover Rework +* *Time for Issues Resolution*	1 5 Days
2	*Design Complexity* *Mean Time to Discover Rework +* *Time for Issues Resolution*	1 20 Days
3	*Design Complexity* *Mean Time to Discover Rework +* *Time for Issues Resolution*	2 5 Days
4	*Design Complexity* *Mean Time to Discover Rework +* *Time for Issues Resolution*	2 20 Days

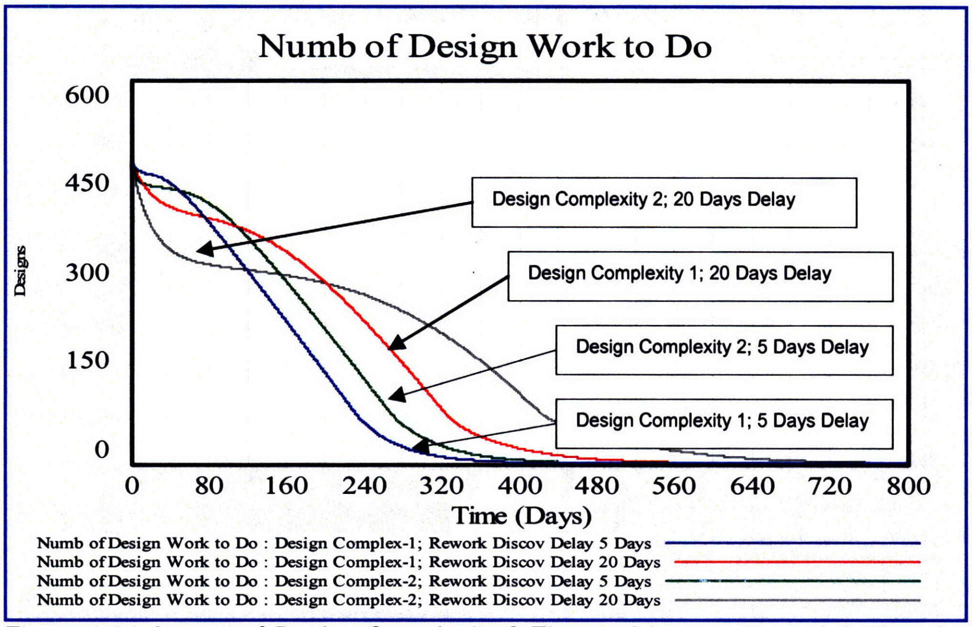


Figure 4.24: Impact of *Design-Complexity & Time-to-Discover-Rework & Time-for-Issues-Resolution* on *Number of Design Work to Do*

Figure 4.24 shows the S-curves for *Numb-of-Design-Work-to-Do* for *Design-Complexity* = 1 and 2, and *Mean-Time-to-Discover-Rework & Time-for-Issues-Resolution* = 5 and 20 Days. The behavior of the curves are similar to the analysis presented in the last section, and the curve for *Design-Complexity* =1, and *Mean-Time-to-Discover-Rework & Time-for-Issues-Resolution* = 5 and 20 Days delay (Blue and Red lines) are same as discussed in the last section. Notice the larger delay for *Design-Complexity* =2 and delay = 20 Days (Gray line).

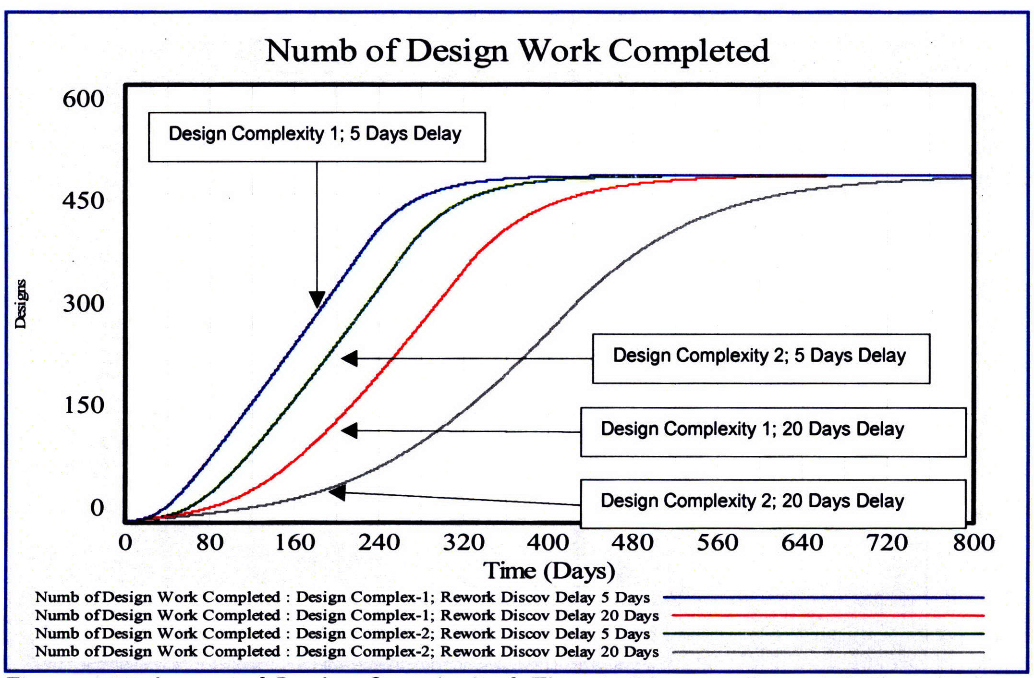


Figure 4.25: Impact of *Design-Complexity & Time-to-Discover-Rework & Time-for-Issues-Resolution* on *Number of Design Work Completed*

Figure 4.25 shows the *Numb-of-Design-Work-Completed* for the 4 cases. Note that the case for *Design-Complexity* = 1 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days (Blue line) finishes first, while the case for *Design-Complexity* = 2 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days (Gray line) finishes latest.

Figure 4.26 shows the *Cumulative-Work-Done* for the 4 cases. The case for *Design-Complexity* = 1 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days (Blue line) results in the smallest cumulative work done, while the case for *Complexity* = 2 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days (Gray line) results in the highest cumulative work done.

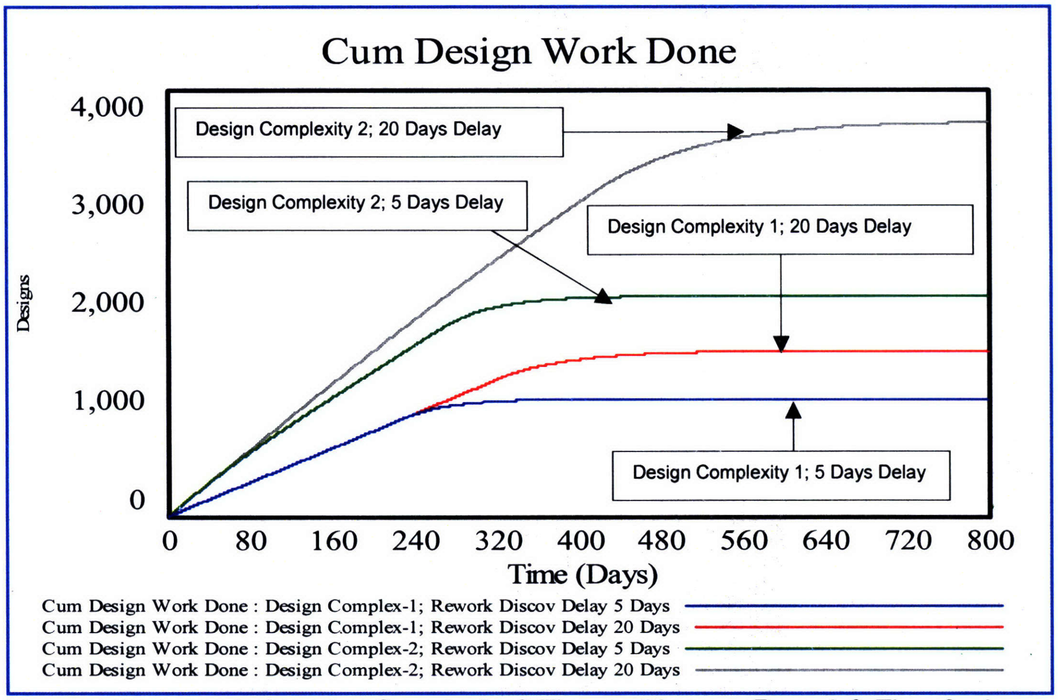


Figure 4.26: Impact of *Design-Complexity & Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on *Cumulative Design Work Done*

Figure 4.27 shows the *Numb-of-Engineering-Changes (EC)* generated for the 4 cases. The case for *Design-Complexity* = 1 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days (Blue line), generates 132% of EC. The case for *Design-Complexity* = 1 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days (Red line), generates 226% of EC. The case for *Design-Complexity* = 2 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days (Green line), generates 334% of EC. The case for *Design-Complexity* = 2 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days (Gray line), generates 680% of EC.

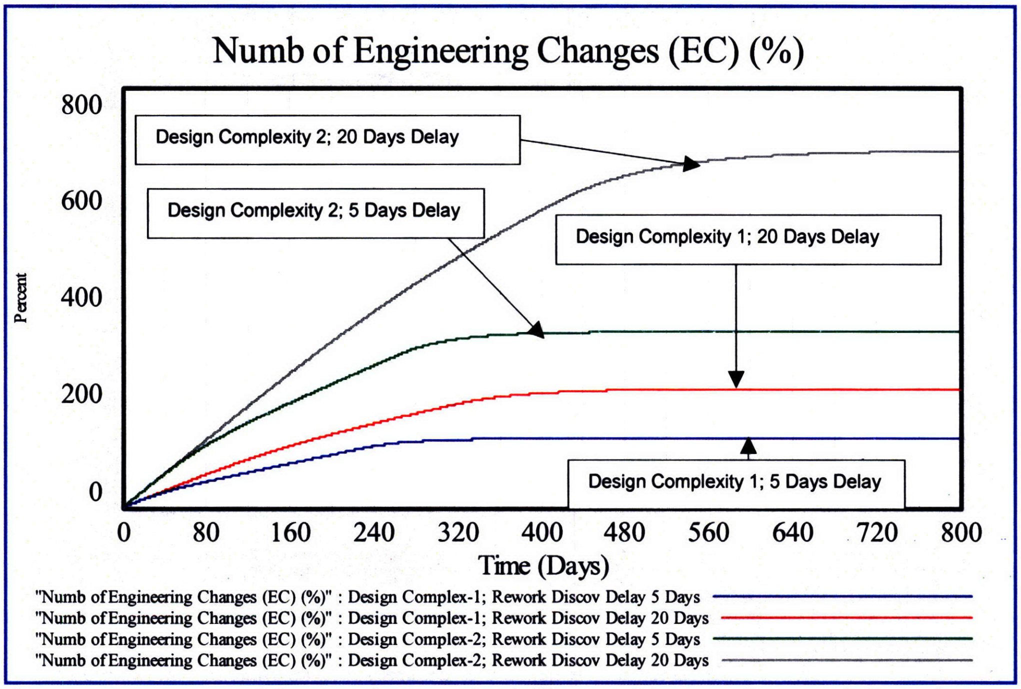


Figure 4.27: Impact of *Design-Complexity* & *Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on *Number of Engineering Changes*

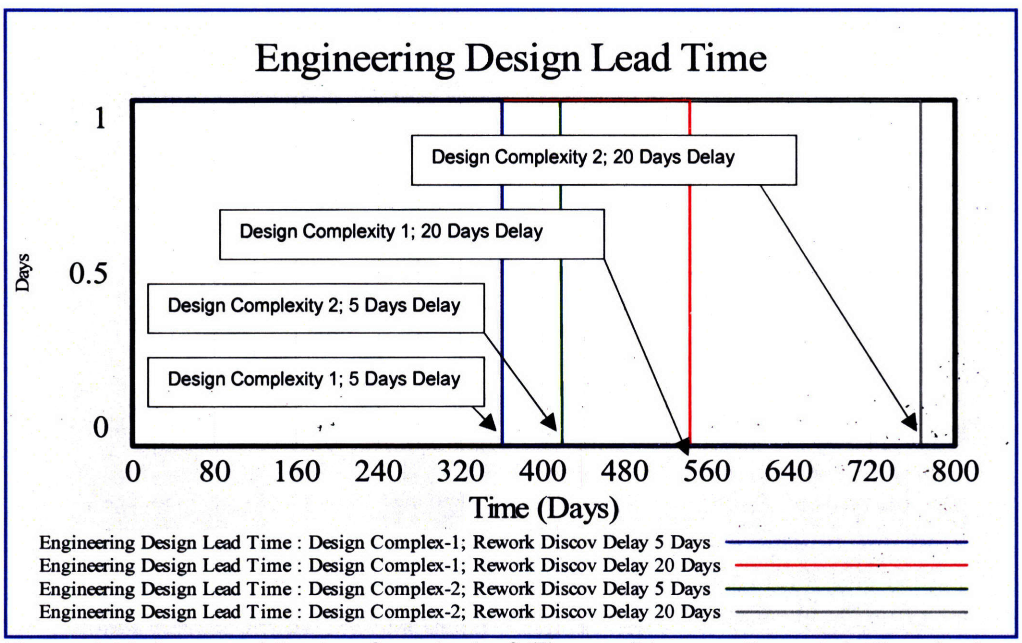


Figure 4.28: Impact of *Design-Complexity* & *Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on *Engineering Design Lead Time*

Figure 4.28 shows the *Engineering-Design-Lead-Time* for the 4 cases. The case for *Design-Complexity* = 1 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days (Blue line), has a Lead Time of 360 Days – the Baseline case. The case for *Design-Complexity* = 1 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days (Red line), has a Lead Time of 545 Days. The case for *Design-*

Complexity* = 2 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days (Green line), has a Lead Time of 419 Days. The case for *Design-Complexity* = 2 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days (Gray line) has a Lead Time of 769 Days.

Figure 4.29 shows the *Cumulative-Labor Cost* for the 4 cases. The case for *Design-Complexity* = 1 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days (Blue line), has a Labor cost of $144,158 – the Baseline case. The case for *Design-Complexity* = 1 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days (Red line), has a Labor cost of $217,608. The case for *Design-Complexity* = 2 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days (Green line), has a Labor cost of $167,459. The case for *Design-Complexity* = 2 and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days (Gray line) has a Labor cost of $307,342.

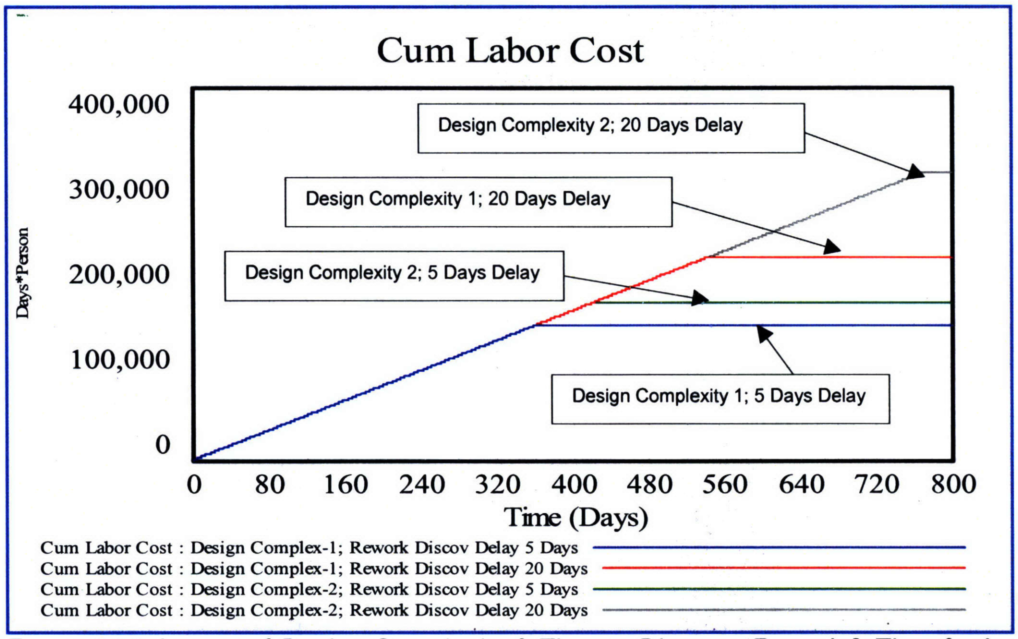


Figure 4.29: Impact of *Design-Complexity* & *Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on *Cumulative Labor Cost*

Figure 4.30 shows the combined impact of *Design-Complexity* and *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on *Quality* for the 4 cases. *Quality* is seen to be negatively impacted by *Design-Complexity* and the delay in Rework discovery and Issues Resolution. *Quality* is seen to decrease as the *Design-Complexity* and the *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* increase.

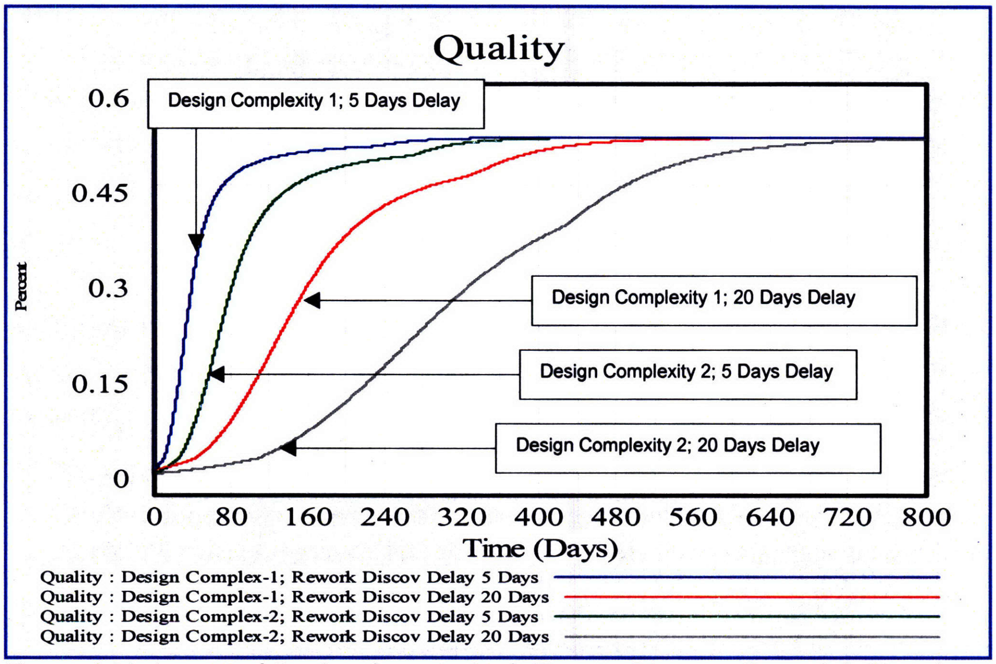


Figure 4.30: Impact of *Design-Complexity* & *Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on Quality

4.5. Impact of *Productivity* on Engineering Change Generation

In this section we employ the model to study the impact of *Productivity* on rework generation by simulating the model for different values of *Productivity*. In Table 4.7 the *Max-Productivity* is the variable that is changing values from 0.009 Designs/Person-Day (90% of the Baseline value of 0.01) to 0.011 Designs/Person-Day (110% of the Baseline value of 0.01) as shown.

Table 4.7: Sensitivity Analysis - Impact of *Productivity* on Engineering Change Generation

No	Variable Name	Baseline Values
1	*Ref Quality*	52% - Baseline
2	***Ref-Productivity***	**0.009, 0.01, 0.011 Designs/Person-Day**
3	*Design Complexity*	1
4	*Initial Numb of Design Work to Do*	474 Designs
5	*Mean Time to Discover Rework +*	5 Days
6	*Time for Issues Resolution*	
7	*Minimum Time to Perform a Task*	20 Days
8	*Relative Quality of New Hires*	0.5
9	*Relative Productivity of New Hires*	0.5
10	*Max Staff Capacity*	400
11	*Numb of Experienced Staff*	200 persons
12	*Over Time Staff*	100 persons
13	*Over Time Quality Decrease Rate*	1/1000 per Day
14	*Over Time Productivity Decrease Rate*	1/1000 per Day
15	*Hiring Rate*	10 persons/month
16	*Time for New Hires To Gain Experience*	90 Days

Figure 4.31 shows the S-curves for the decrease of *Numb-of-Design-Work-to-Do* for the three values of *Ref-Productivity*. It can be seen that there is no significant difference between the three curves. This is because *Productivity* has no impact on the generation of Engineering Change. Therefore the decrease rate of the S-curves arise solely from the corresponding rates of work accomplishments for the difference *Ref-Productivity* values. The highest *Ref-Productivity* of 0.011 produces the highest decrease rate while the lowest *Ref-Productivity* of 0.009 results in the lowest decrease rate.

Figure 4.32 shows the S-curves for the increase of *Numb-of-Design-Work-Completed* for the three values of *Ref-Productivity.* As with the *Numb-of-Design-Work-to-Do,* it can be seen that there is no significant difference between the three curves due to the fact that *Productivity* has no impact on the generation of Engineering Change. Therefore the increase rate of the S-curves arise solely from the corresponding rates of work accomplishments for the difference *Ref-Productivity* values. The highest *Ref-Productivity* of 0.011 produces the highest increase rate while the lowest *Ref-Productivity* of 0.009 results in the lowest increase rate.

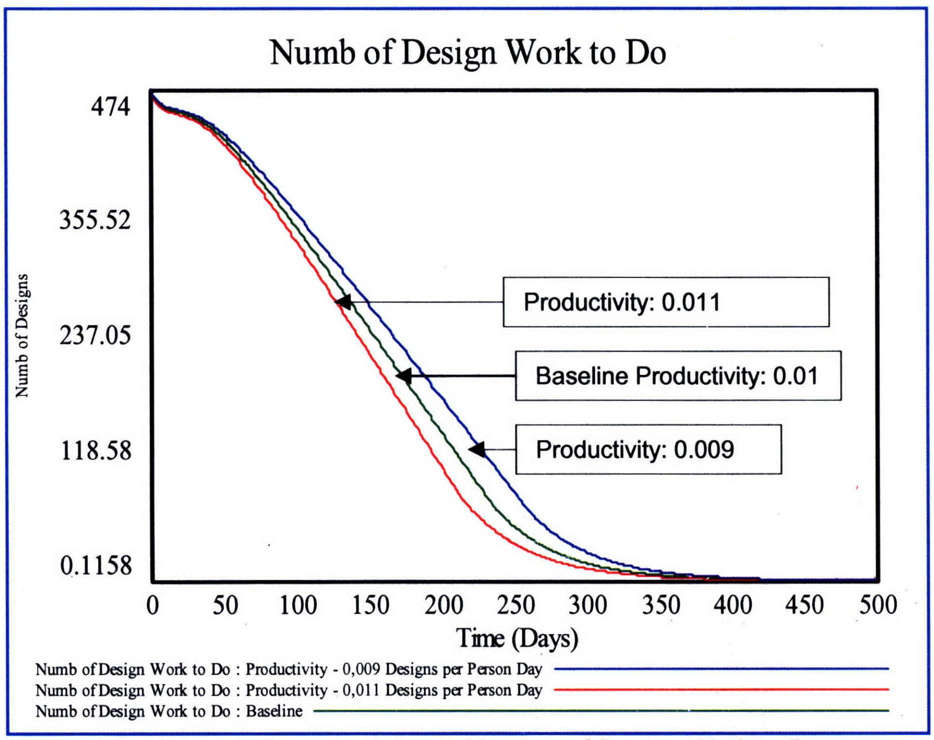


Figure 4.31: Impact of *Productivity* on *Number of Design Work to Do*

Figure 4.33 shows the *Cumulative-Design-Work-Done* for the three values of *Ref-Productivity*. As can be seen, *Productivity* has little impact on the Cumulative work done since *Productivity* does not impact Rework generation

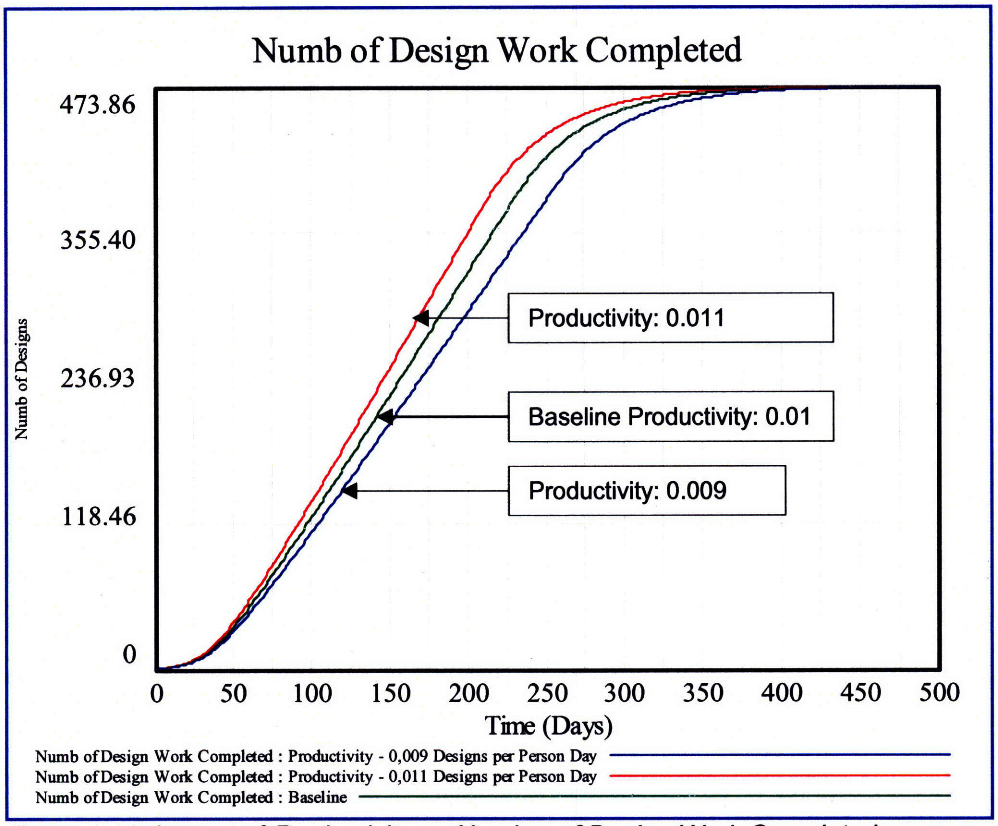


Figure 4.32: Impact of *Productivity* on *Number of Design Work Completed*

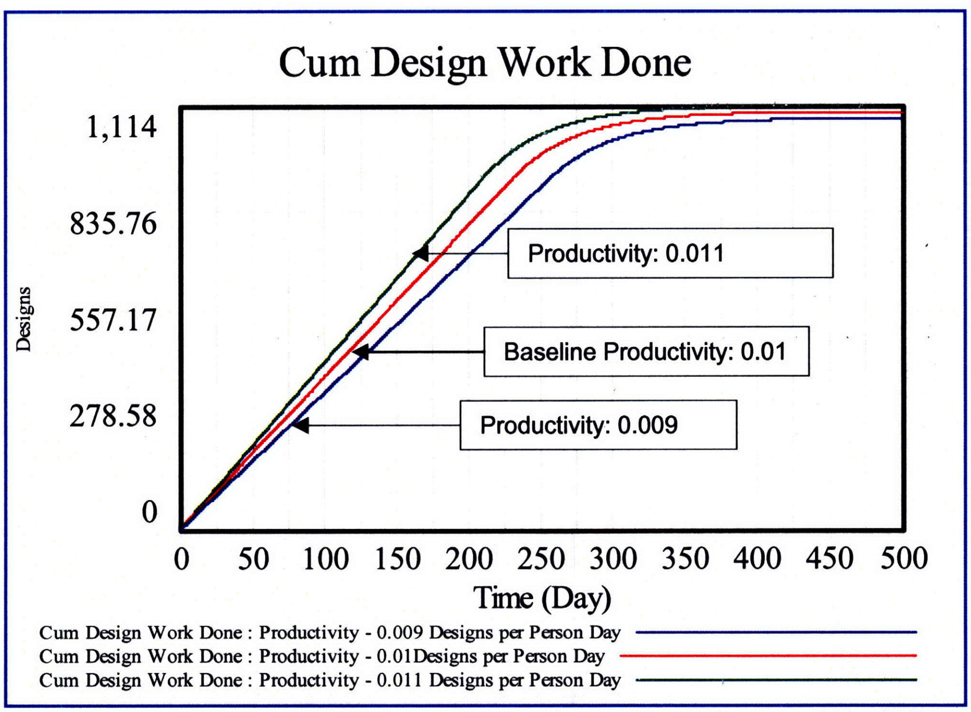


Figure 4.33: Impact of *Productivity* on Cumulative Design Work Done

Figure 4.34 shows the *Numb-of-Engineering-Changes (EC)* for the three values of *Ref-Productivity*. For
Baseline case *Ref-Productivity* 0.01 Designs per Person-Days; EC = 131%
Ref-Productivity 0.009 Designs per Person-Days; EC = 128%
Ref-Productivity 0.011 Designs per Person-Days; EC = 135%

We see that *Productivity* has no impact in generating Engineering-Changes

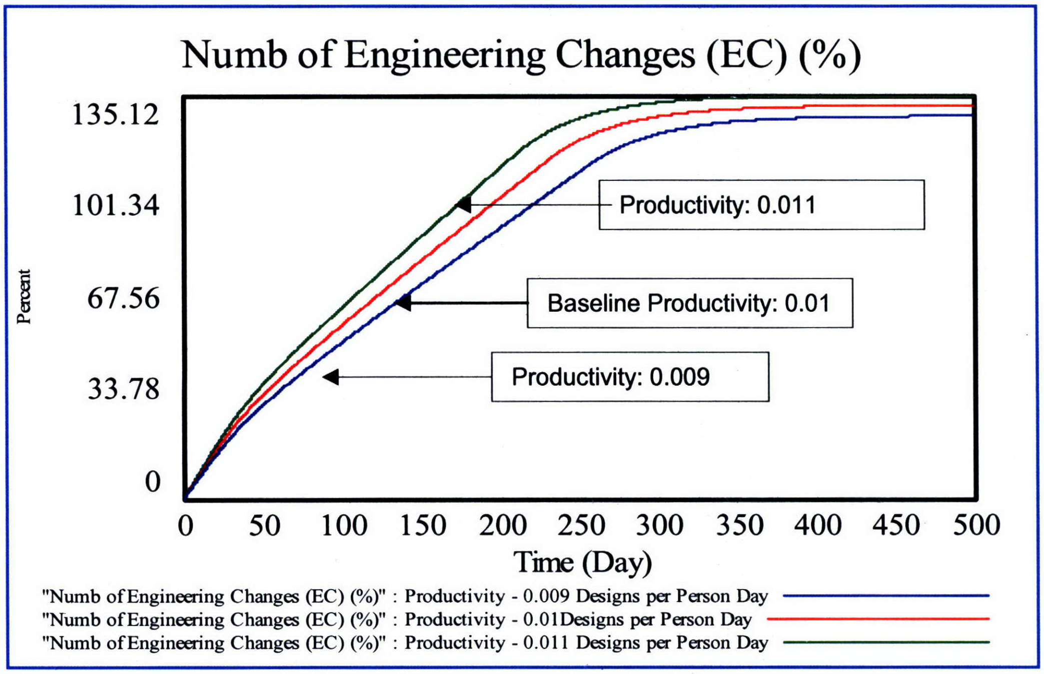


Figure 4.34: Impact of *Productivity* on Numb of Engineering Changes

Figure 4.35 shows the corresponding *Engineering-Design-Lead-Time* for the three cases.
Baseline case *Ref-Productivity* 0.01 Designs per Person-Days; Lead Time = 360 Days
Ref-Productivity 0.009 Designs per Person-Days; Lead Time = 382 Days
Ref-Productivity 0.011 Designs per Person-Days; Lead Time = 344 Days

We see that Productivity has an impact on Lead Time with the highest *Productivity* of 0.011 giving the shortest and the lowest *Productivity* of 0.009 the longest Lead Time.

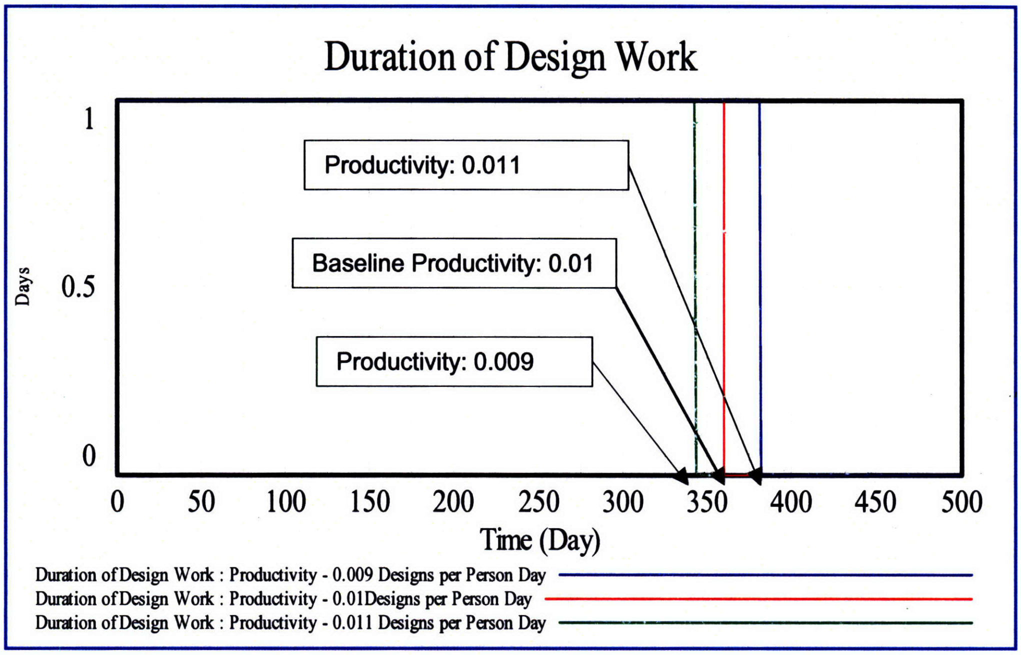


Figure 4.35: Impact of *Productivity* on *Engineering-Design-Lead-Time*

4.6. Impact of Over Time on *Quality, Productivity* & *Engineering-Design-Lead-Time and Labor-Cost*

Table 4.8: Simulating the impact of Over Time on Quality, Productivity, Lead Time & Labor Cost

No	Variable name	Baseline Values
1	*Ref-Quality*	52% - Baseline
2	*Ref-Productivity*	0.01 Designs/Person-Day
3	*Design-Complexity*	1
4	*Initial-Numb-of-Design-Work-to-Do*	474 Designs
5	*Mean-Time-to-Discover-Rework*	4 Days
6	*Time-for-Issues-Resolution*	1 Days
7	*Minimum-Time-to-Perform-a-Design*	20 Days
8	*Relative-Quality-of-New-Hires*	0.5
9	*Relative Productivity-of-New-Hires*	0.5
10	*Max-Staff-Capacity*	400
11	*Numb-of-Experienced-Staff*	200 persons
12	*Over-Time-Staff*	100 persons
13	***Over-Time-Quality-Decrease-Rate***	***1/1,000 per Day***
14	***Over-Time-Productivity-Decrease-Rate***	***1/1,000 per Day***
15	*Hiring-Rate*	10 persons/month
16	*Time-for-New-Hires-To-Gain-Experience*	90 Days

In this section we employ the model to study the impact of Overtime work on *Productivity* and *Quality* on rework generation. In Table 4.8 the *Over-Time-Productivity-Decrease-Rate* and the *Over-Time-Quality-Decrease-Rate* are the variable that are changing values as shown. Both variables are assumed to decrease at a rate of 1/1,000 per Day = 0.1% per day.

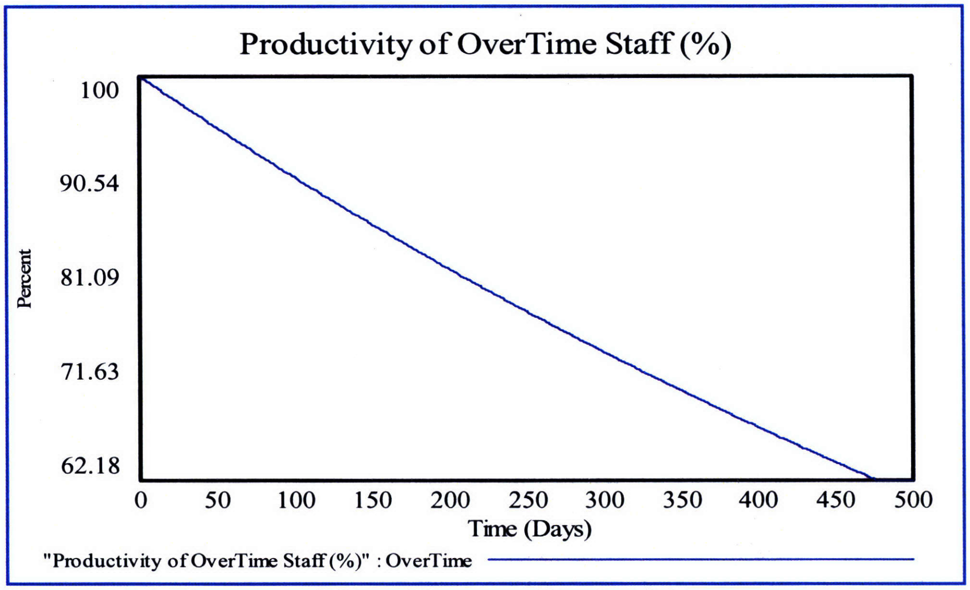


Figure 4.36: Impact of Over Time on Productivity

Figure 4.36 shows the decline of *Productivity* of the staff as result of working Over Time. It shows that if *Productivity* of a staff decreases at a rate of 0.1% per day, then in about 476 days, the *Productivity* of a staff will be 62% of it value on day one.

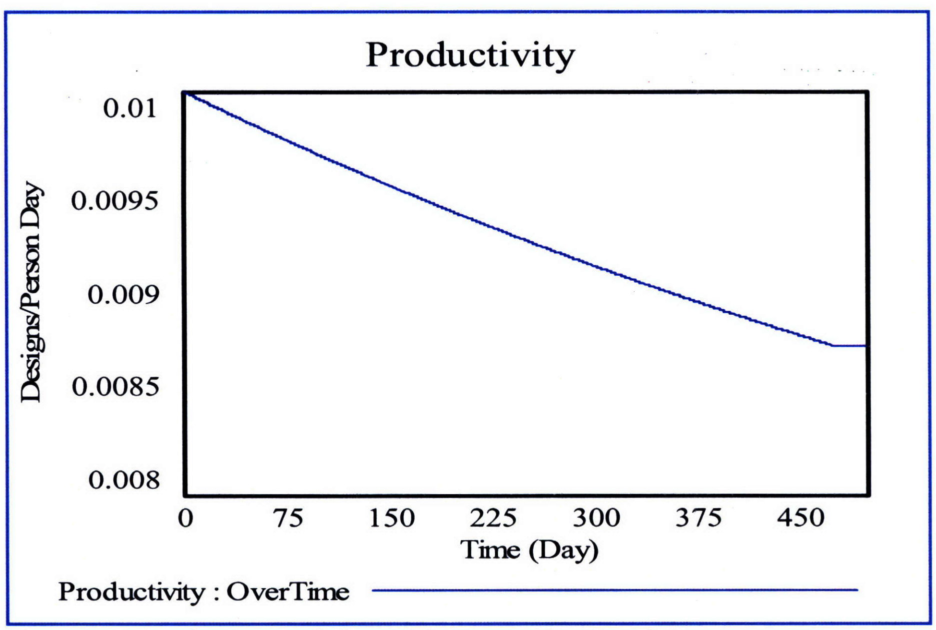


Figure 4.36: Impact of Over Time on Productivity

Figure 4.37 shows that the *Productivity* of the entire staff decreases from 0.01 to about 0.0087 as result of working Overtime. This corresponds to a decline in *Productivity* of about 13%.

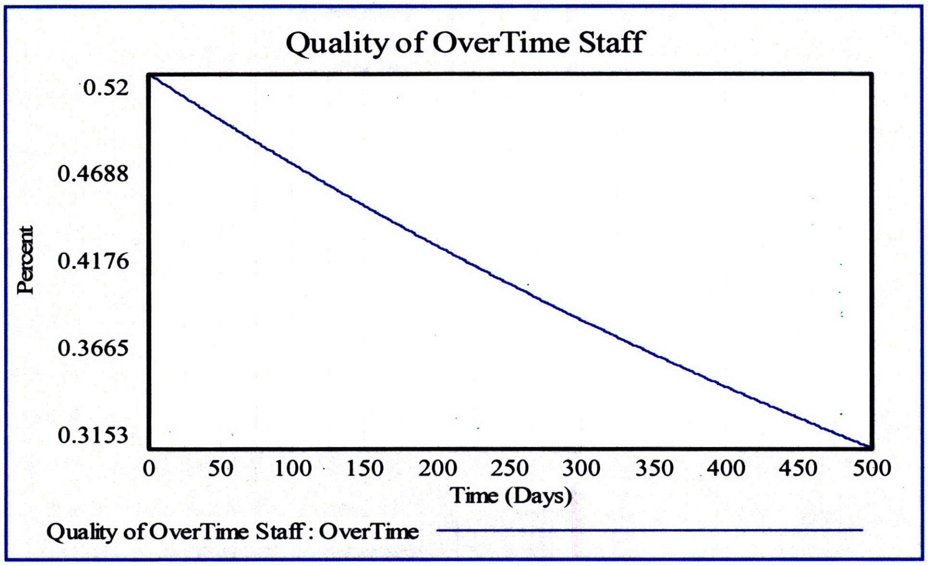


Figure 4.37: Impact of Over Time on Quality

Figure 4.38 shows the decline of *Quality* of the staff as a result of working Over Time. The *Quality* declines from 0.52 to about 0.32 in 476 days.

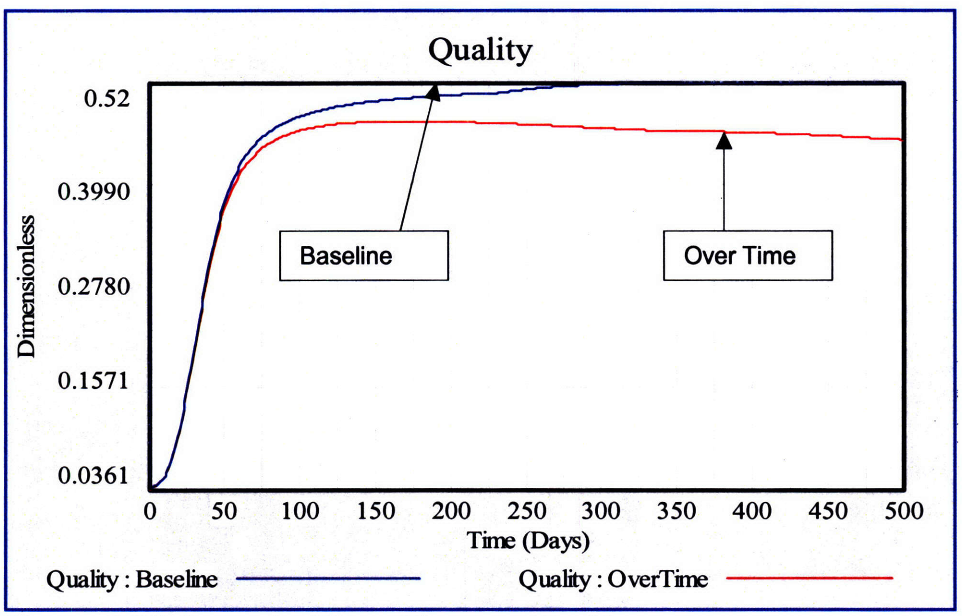


Figure 4.38: Impact of Over Time on Quality

Figure 4.39 shows the Engineering Design Lead Time for Over Time to be 476 days.

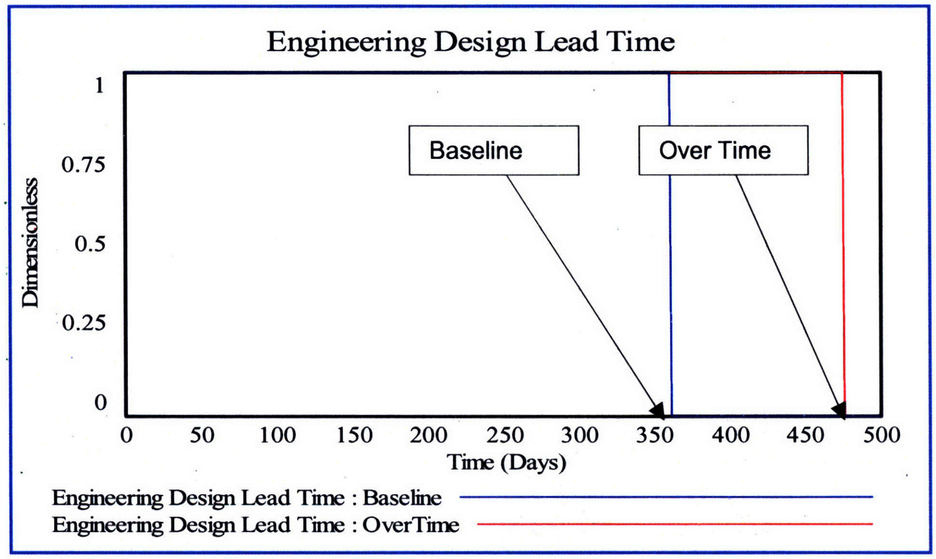


Figure 4.39: Impact of Over Time on Lead Time

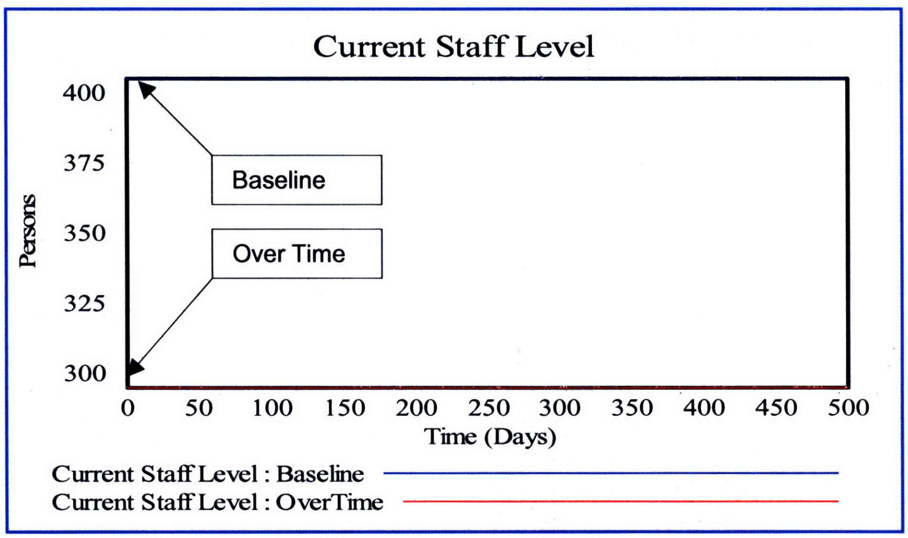


Figure 4.40: Impact of Over Time on Staff Levels

Figure 4.40 shows the Baseline Staff Level of 400 and the Over Time Staff Level of 300 (200 Regular + 100 Over Time).

4.7. Impact of Hiring on *Quality, Productivity* & *Engineering-Design-Lead-Time and Labor-Cost*

In this section we employ the model to study the impact of Hiring on *Productivity* and *Quality*. In Table 4.9 the *Hiring-Rate*, the *Time-for-New-Hires-To-Gain-Experience, Relative-Quality-of-New-Hires* and *Relative Productivity-of-New-Hires* are the variable that are changing values as shown.

Table 4.9: Simulating the impact of Hiring on Quality, Productivity, Lead Time & Labor Cost

No	Variable name	Baseline Values
1	*Max-Quality*	40%, 52% - Baseline, 60%
2	*Max-Productivity*	0.01 Designs/Person-Day
3	*Design-Complexity*	1
4	*Initial-Numb-of-Design-Work-to-Do*	474 Designs
5	*Mean-Time-to-Discover-Rework*	4 Days
6	*Time-for-Issues-Resolution*	1 Days
7	*Minimum-Time-to-Perform-a-Design*	20 Days
8	***Relative-Quality-of-New-Hires***	***26% (=50% of 52%)***
9	***Relative Productivity-of-New-Hires***	***0.005Designs/Person-Day (=50% of 0.01)***
10	*Max-Staff-Capacity*	400
11	*Numb-of-Experienced-Staff*	200 persons
12	*Over-Time-Staff*	100 persons
13	*Over-Time-Quality-Decrease-Rate*	*1/1,000 per Day*
14	*Over-Time-Productivity-Decrease-Rate*	*1/1,000 per Day*
15	***Hiring-Rate***	***10 persons/month***
16	***Time-for-New-Hires-To-Gain-Experience***	***90 Days***

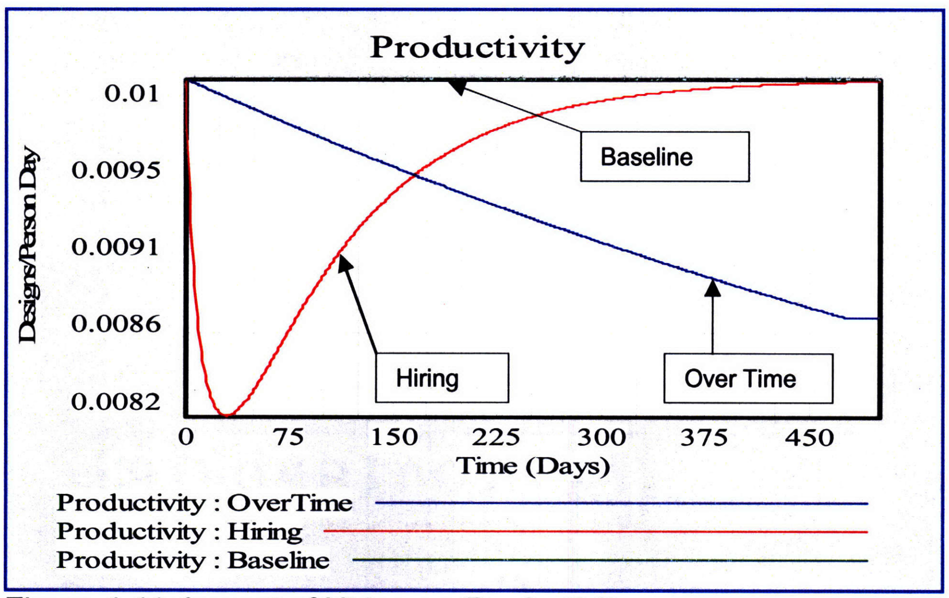


Figure 4.41: Impact of Hiring on *Productivity*

Figure 4.41 shows the impact of Hiring on *Productivity*. Note that the *Productivity* curve for Hiring (Red line) first dips due to the relative inexperience of new Hires – in this case the *Productivity* of new Hires is assumed to be only 50% that of experienced staff. However, as the new hires begin to gain experience – again, in this case it is assumed that a new hire becomes experienced in 90 Days – the *Productivity* begins to climb again and eventually attains the maximum *Productivity* of experienced staff. How fast the productivity increases depends on how aggressive the training the new Hires are given. The Over Time curve (Blue line) was discusses in the last section.

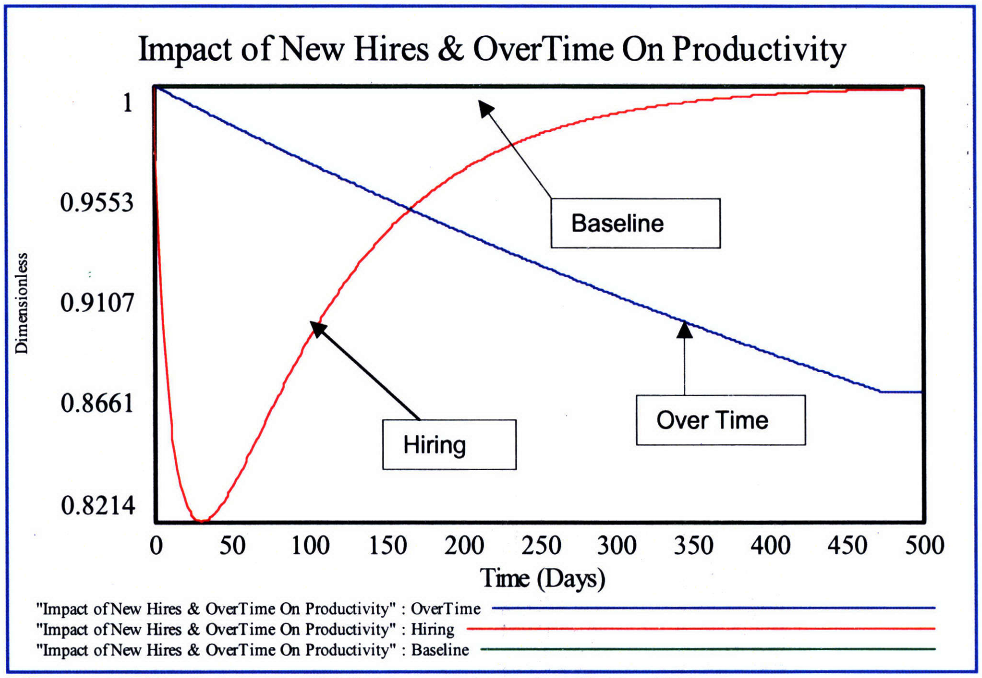


Figure 4.42: Impact of Hiring on *Productivity (%)*

Figure 4.42 shows the *Productivity* curve for Hiring as a percentage. This indicates that the *Productivity* dips to about 82% as a result of the inexperience of new Hires before starting to climb again as shown.

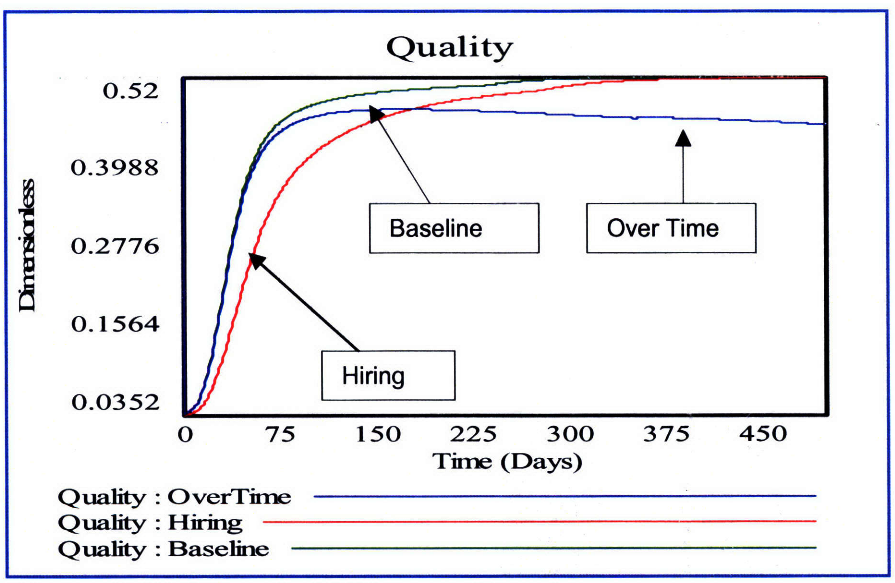


Figure 4.43: Impact of Hiring on *Quality*

Figure 4.43 shows the impact of Hiring on *Quality*. As with *Productivity*, the *Quality* decreases as a result of Hiring (Red curve). *Quality* first dips due to the relative inexperience of new Hires – in this case the *Quality* of new Hires is assumed to be only 50% of experienced staff. However, as the new Hires begin to gain experience the *Quality* begins to improve again and eventually attains the maximum *Quality* of experienced staff. How fast the *Quality* increases depends as with *Productivity* on how aggressive the training the new hires are given.

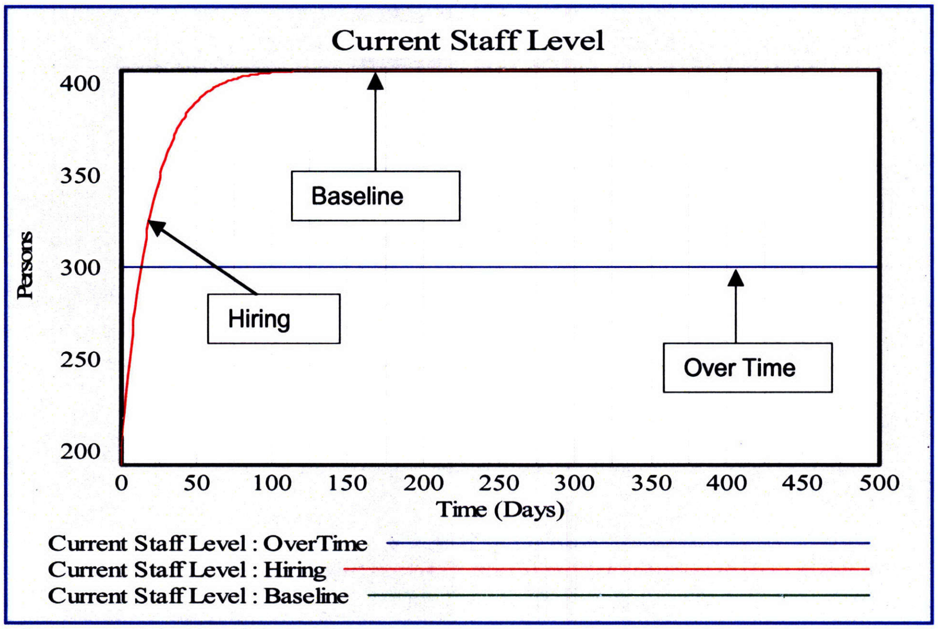


Figure 4.44: Staff Levels

Figure 4.44 shows that the staff levels started from 200 experienced staff and increased to 400 over a period of about 100 Days from Hiring.

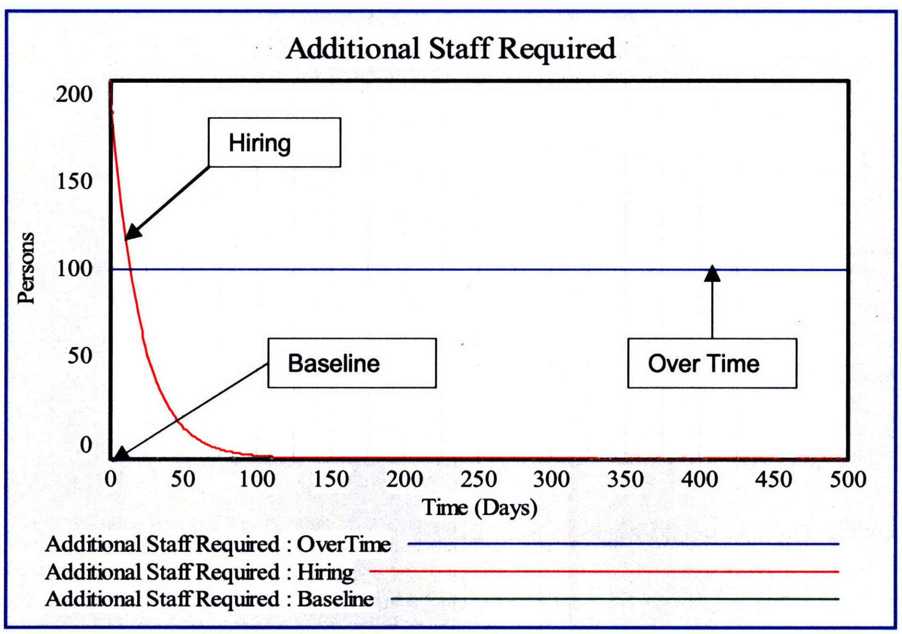


Figure 4.45: Additional Staff Required

Figure 4.45 shows that correspondingly, the *Additional-Staff-Required* decreases from an initial value of 200 to zero over the 100 Day period as Hiring went on.

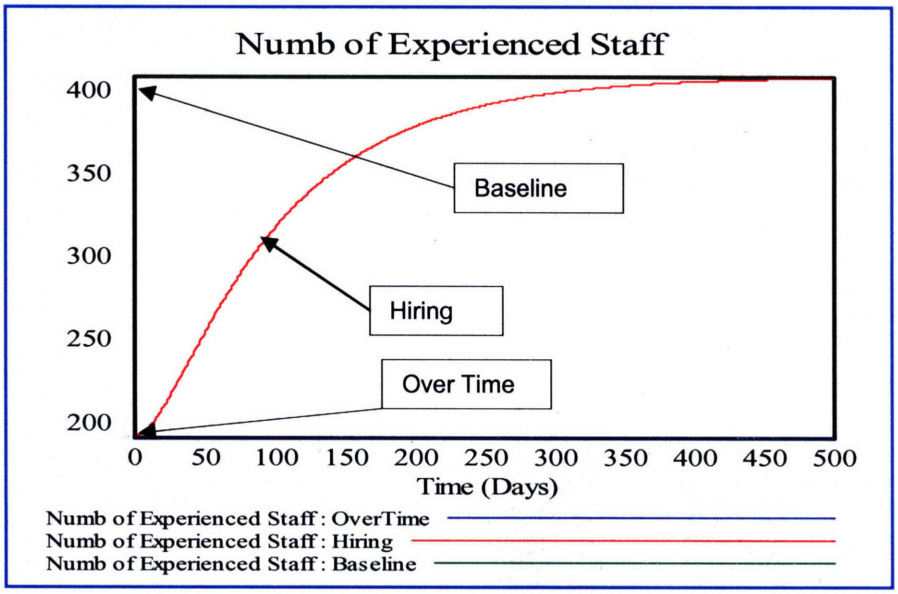


Figure 4.46: Growth of Experienced Staff

Figure 4.46 shows that the growth profile of the Experience staff. Note that this profile is very different from the growth in staff level shown in Figure 4.44.

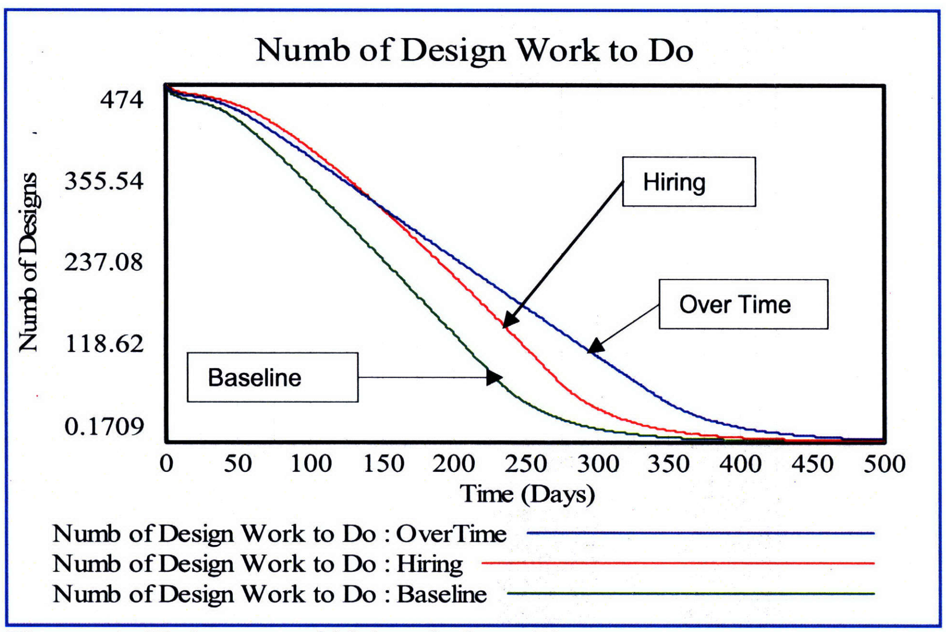


Figure 4.47: Impact of Hiring & Over Time on *Numb of Design Work to Do*

Figure 4.47 shows the curves for the *Numb-of-Design-Work-to-Do* for the Baseline, Over Time and Hiring cases.

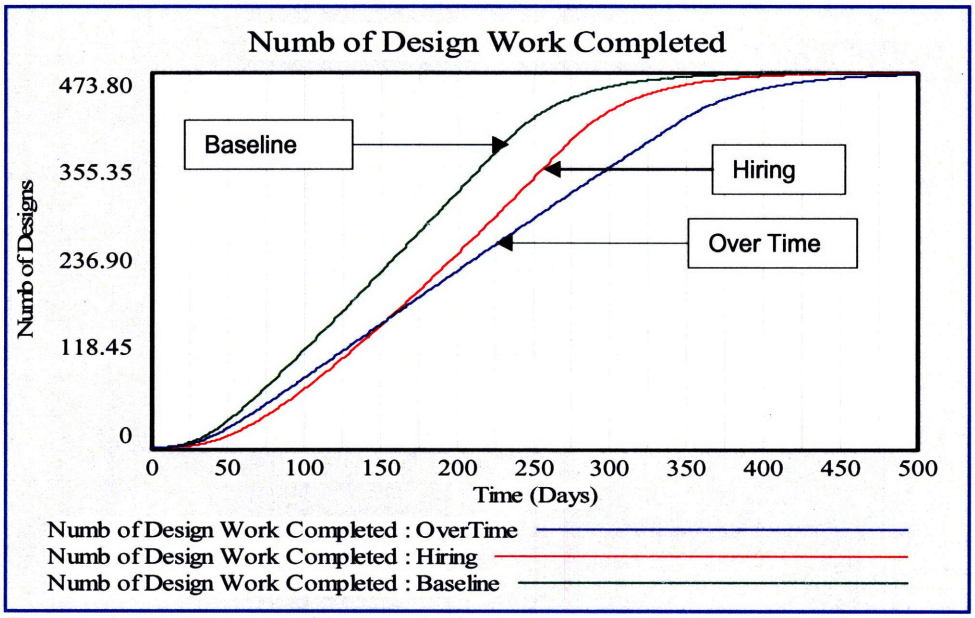


Figure 4.48: Impact of Hiring & Over Time on *Numb of Design Work Completed*

Figure 4.48 shows the curves for the *Numb-of-Design-Work-Completed* for the Baseline, Over Time and Hiring cases.

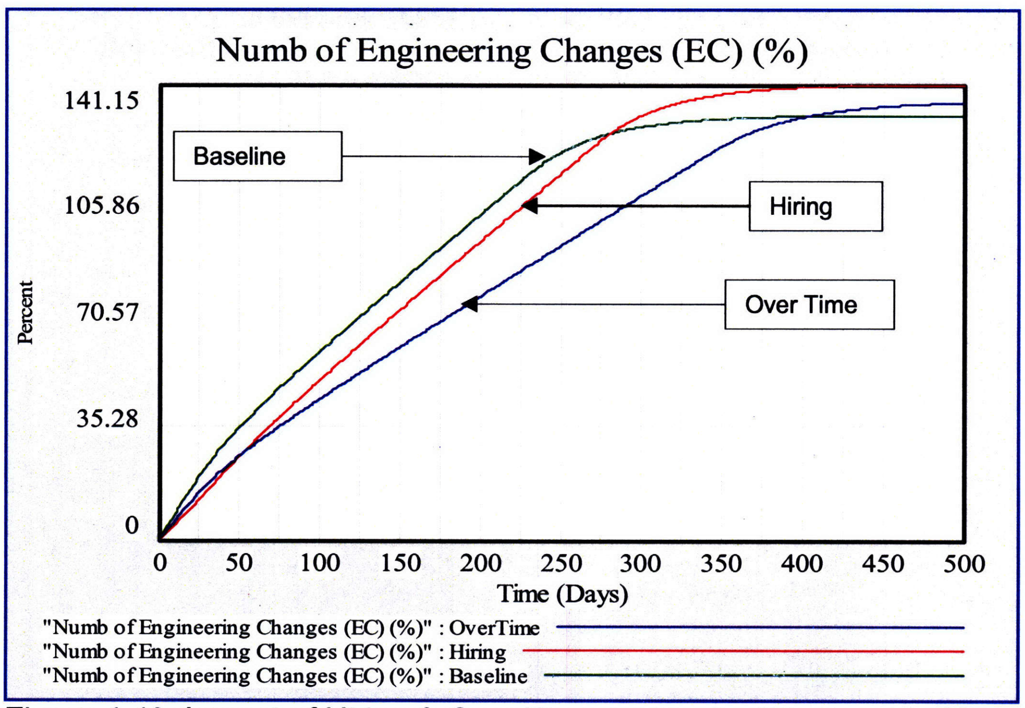


Figure 4.49: Impact of Hiring & Over Time on *Numb of Engineering Changes*

Figure 4.49 shows the curves for the *Numb-of-Engineering-Changes* for the Baseline case, Over Time and Hiring cases. Note that Hiring generates the most Engineering Changes due to lower *Quality* work by new Hires in comparison to experienced staff.

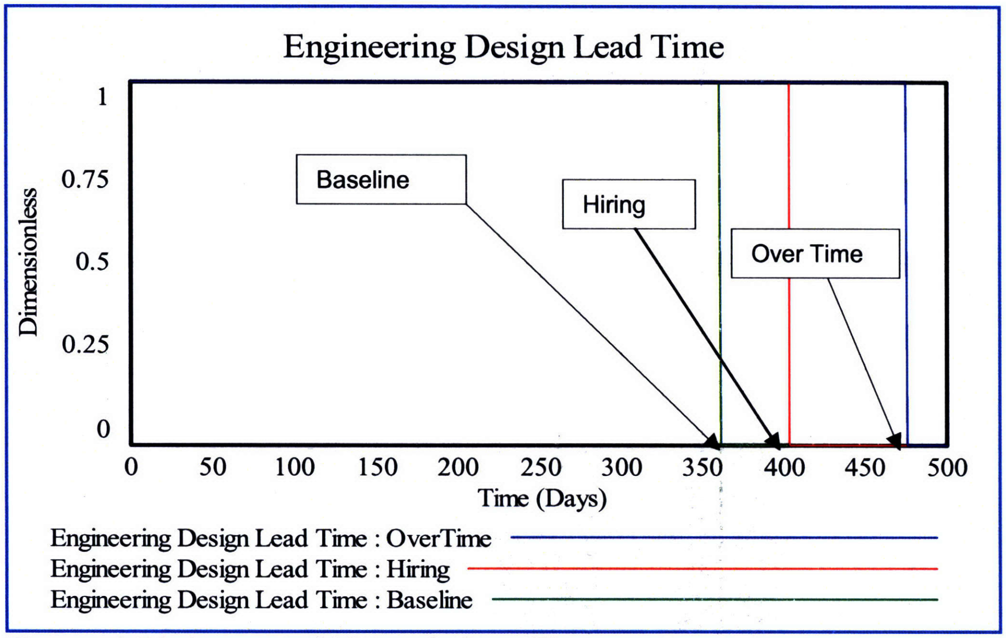


Figure 4.50: Impact of Hiring & Over Time on *Lead Time*

Figure 4.50 shows the *Engineering-Lead-Time* for the Baseline case (360 Days), Over Time (476 Days) and Hiring (409 Days). Over Time results in the longest *Lead Time.* Though work *Quality* of Over Time staff is a contributing factor, the much longer *Lead Time* is due mainly to the lower number of staff. Staff levels are: Over Time - 300 staff, Hiring and Baseline – 400.

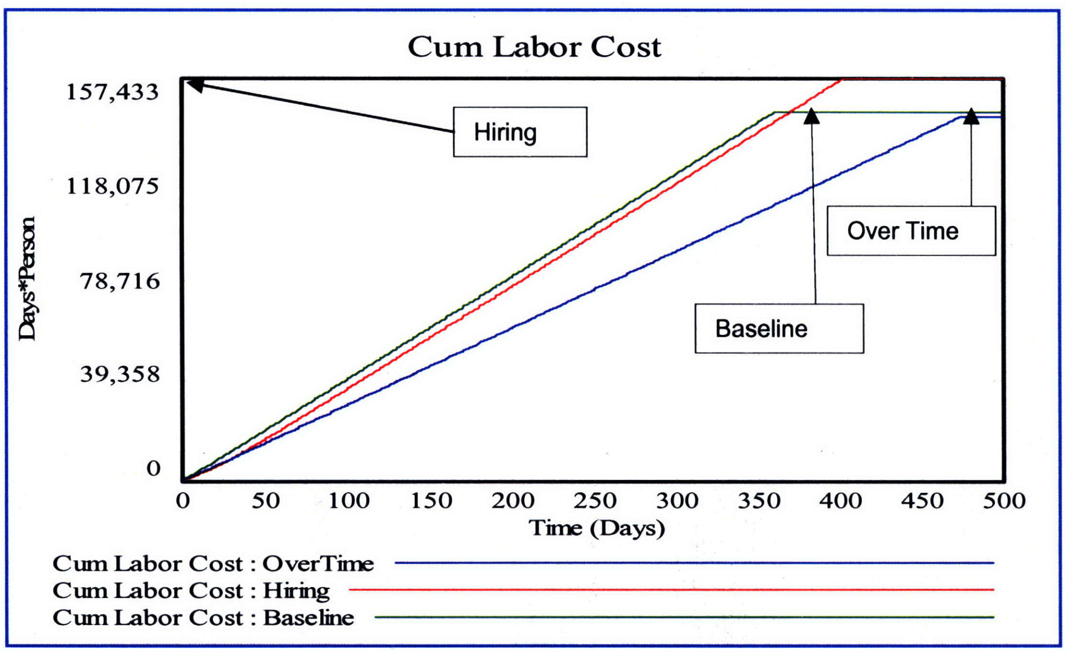


Figure 4.51: Impact of Hiring & Over Time on *Labor Cost*

Figure 4.51 shows the *Cumulative-Labor-Cost* for the Baseline case ($144,158), Over Time ($142,525) and Hiring ($157,433). Again, Over Time results in lowest Labor Cost because of lower staff levels.

4.8. Combined Impact of Hiring & Over Time on *Quality, Productivity* & *Engineering-Design-Lead-Time and Labor-Cost*

In this section we employ the model to study the combined impact of Hiring and Over Time on *Productivity* and *Quality*. In Table 4.10 the *Hiring-Rate*, the *Time-for-New-Hires-To-Gain-Experience, Relative-Quality-of-New-Hires* and *Relative Productivity-of-New-Hires, Over-Time-Staff, Over-Time-Quality-Decrease-Rate, Over-Time-Productivity-Decrease-Rate* are the variable that are changing values as shown.

Table 4.10: Simulating the Combined impact of Hiring & Over Time on Quality, Productivity, Lead Time & Labor Cost

No	Variable name	Baseline Values
1	*Max-Quality*	40%, 52% - Baseline, 60%
2	*Max-Productivity*	0.01 Designs/Person-Day
3	*Design-Complexity*	1
4	*Initial-Numb-of-Design-Work-to-Do*	474 Designs
5	*Mean-Time-to-Discover-Rework*	4 Days
6	*Time-for-Issues-Resolution*	1 Days
7	*Minimum-Time-to-Perform-a-Design*	20 Days
8	***Relative-Quality-of-New-Hires***	***26% (=50% of 52%)***
9	***Relative Productivity-of-New-Hires***	***0.005Designs/Person-Day (=50% of 0.01)***
10	*Max-Staff-Capacity*	400
11	*Numb-of-Experienced-Staff*	200 persons
12	***Over-Time-Staff***	**100 persons**
13	***Over-Time-Quality-Decrease-Rate***	***1/1,000 per Day***
14	***Over-Time-Productivity-Decrease-Rate***	***1/1,000 per Day***
15	***Hiring-Rate***	***10 persons/month***
16	***Time-for-New-Hires-To-Gain-Experience***	***90 Days***

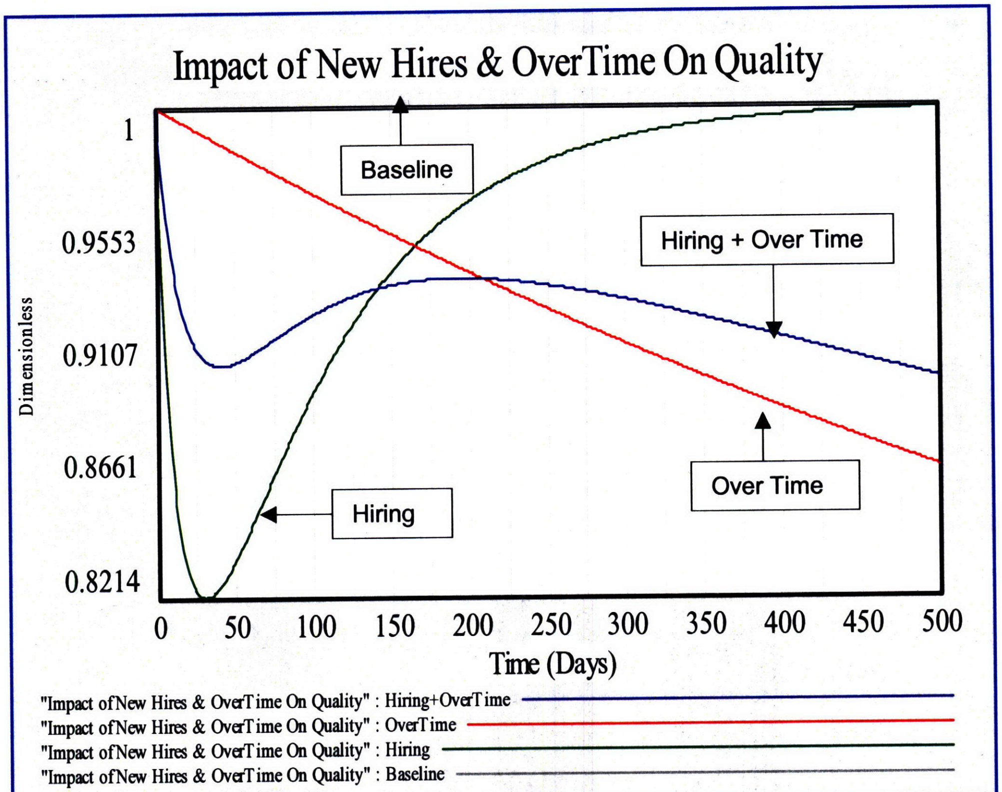


Figure 4.52: The combined impact of Hiring and Over Time on *Productivity* and *Quality*.

Figure 4.52 shows the combined impact of Hiring and Over Time on *Productivity* and *Quality*. The pure Over Time curve (Red line) shows the straight line decline of *Productivity* and *Quality*. Similarly, the pure Hiring curve (Green line) shows that *Productivity* and *Quality* first dip due to the relative inexperience of new Hires – the *Productivity* and *Quality* of new Hires are assumed to be 50% of the *Productivity* and *Quality* Experienced staff. However, as the new Hires begin to gain experience – again, in this case it is assumed that a new Hire becomes experienced in 90 Days – the *Productivity* and *Quality* begins to increase again and eventually attains the maximum *Productivity* and *Quality* of Experienced staff.

The Blue curve shows the combined impact of Hiring and Over Time on *Productivity* and *Quality*. Note that the dip of the combined Hiring and Over Time curve is less severe compared to the pure Hiring curve. The combined Hiring and Over Time curve recovers more quickly but is constrained by the Over Time curve and never attains the *Productivity* and *Quality* of fully Experienced staff.

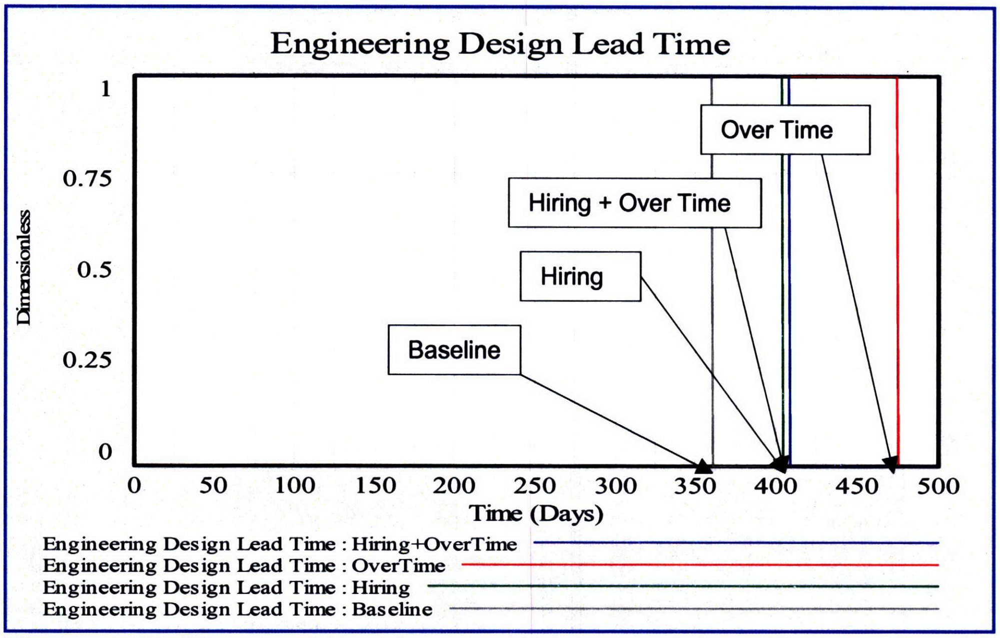


Figure 4.53: The combined impact of Hiring and Over Time on *Lead Time*

Figure 4.53 shows the *Engineering-Lead-Time* for the Baseline case (360 Days), Over Time (476 Days) and Hiring (404 Days), Hiring + Over Time (409 Days). Again, pure Over Time results in the longest Lead Time. Combining Hiring & Over Time is practically the same as pure Hiring.

Figure 4.54 shows the Additional Required Staff. It shows that for pure Hiring, an additional 200 staff are required to attain the 400 Baseline staff level. If Hiring & Over is adopted, then only an additional 100 staff need be hired. Note that the length of time for the hiring is determined by the Hiring rate.

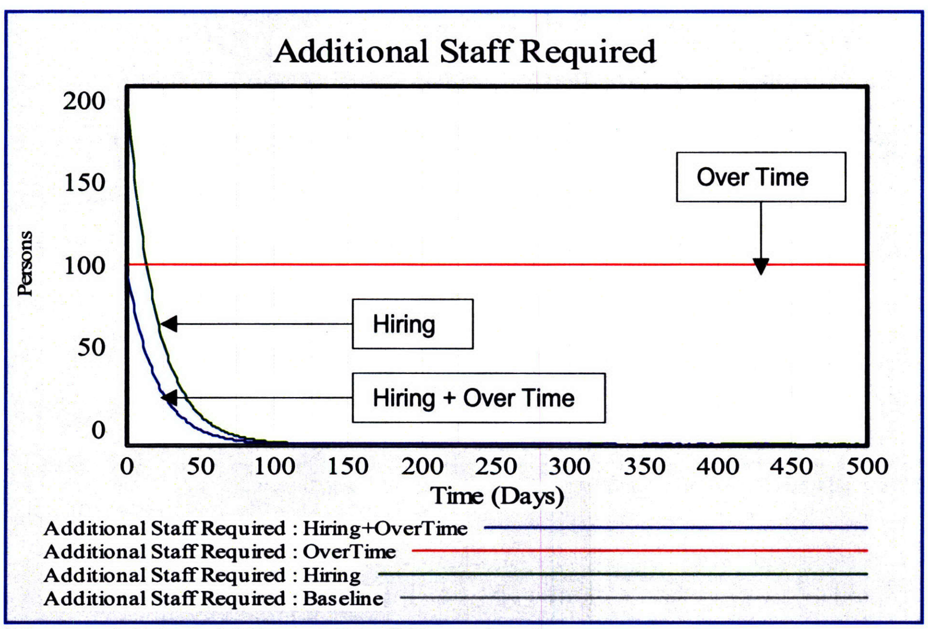


Figure 4.54: Additional Staff Required

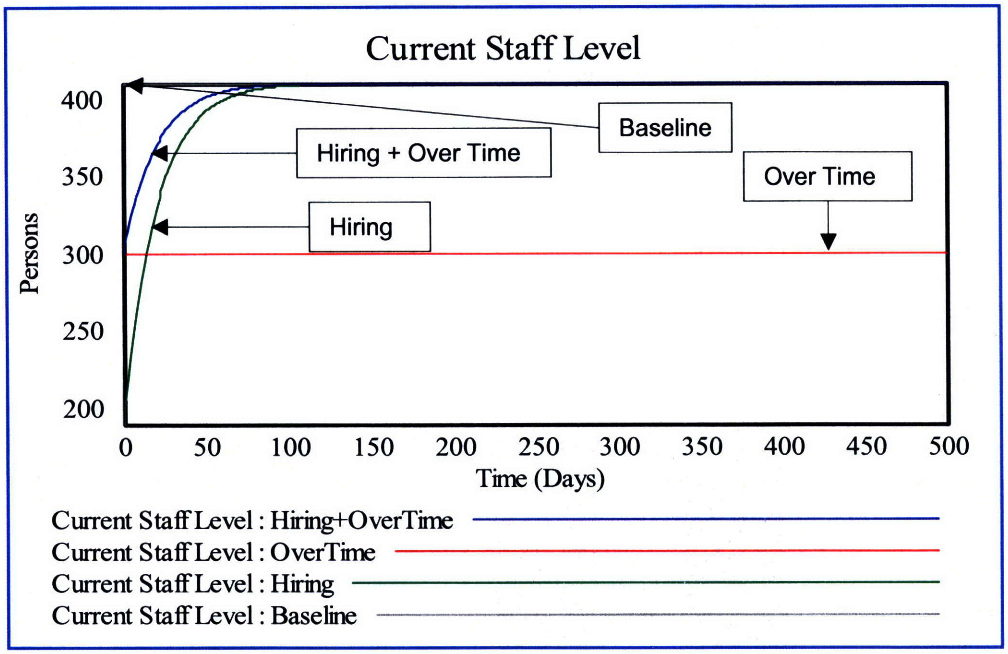


Figure 4.55: Staff Levels

Figure 4.55 shows the Staff Levels. It shows that for pure Hiring, an additional 200 staff are hired over a period of about 100 days to reach the 400 Baseline staff level. If Hiring & Over is adopted, then only100 staff need be hired over the same time period.

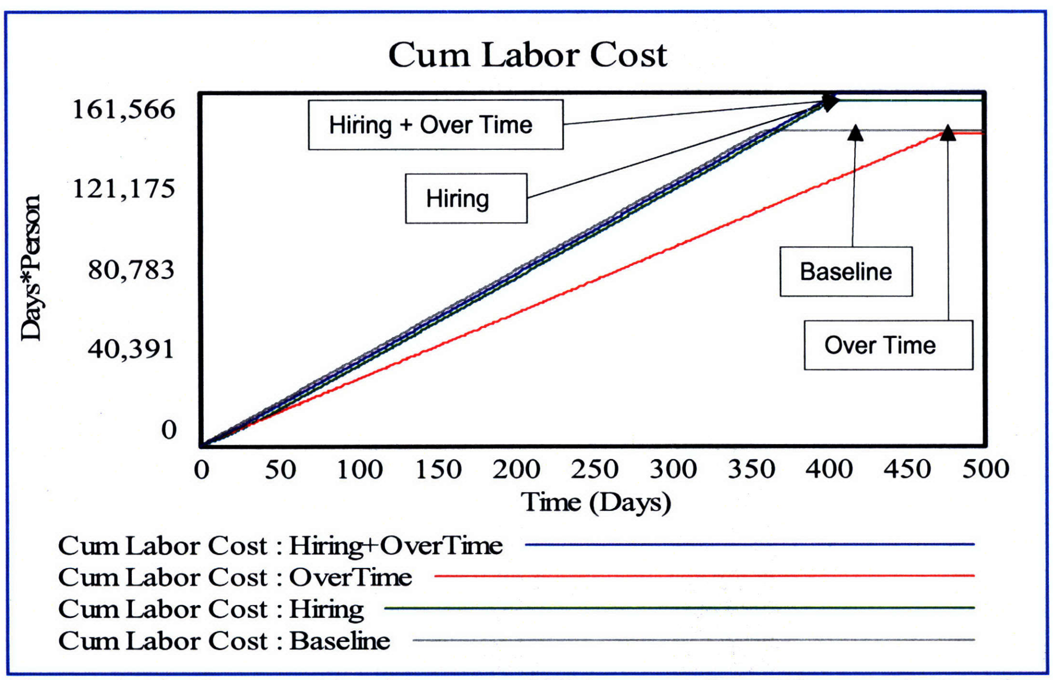


Figure 4.56: The combined impact of Hiring and Over Time on *Labor Cost*

Figure 4.56 shows the *Labor Cost* for the Baseline case ($144,158), Over Time ($142,525) and Hiring (157,433), Hiring + Over Time (161,567). Pure Over Time results in the lowest Labor Cost, while combining Hiring & Over Time results in the highest Labor Cost.

4.9. Impact of *Staff Capacity, Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* on Rework Generation, Lead Time and Labor Cost

Ordinarily, increasing staff capacity will seems to be the surest way to complete the design work on time. However, as this analysis will show, the decrease in Lead Time is not necessarily proportional to staff increase. Figure 4.57, shows the Lead Time of 360 days for the Baseline case (*Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 5 days). Also shown are the Lead Times for staff capacities: 400, 600, 800 and 1,000 (*Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days). The Lead Times are: staff capacity of 400 - 545 days; staff capacity of 600 - 489 days; staff capacity of 800 - 467 days; staff capacity of 1,000 - 457 days.

Notice that for *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 20 days, when staff capacity is increased from 400 to 600, Lead Time decreases by 56 days (=545 – 489). When staff capacity is increased from 600 to 800, Lead Time decreases by 22 days (= 489 - 467). When staff capacity is further increased from 800 to 1,000, Lead Time decreases by only 10 days (= 467 - 457). So we see that an increase in staff capacity is not necessarily accompanied by a proportionate decrease in Lead Time.

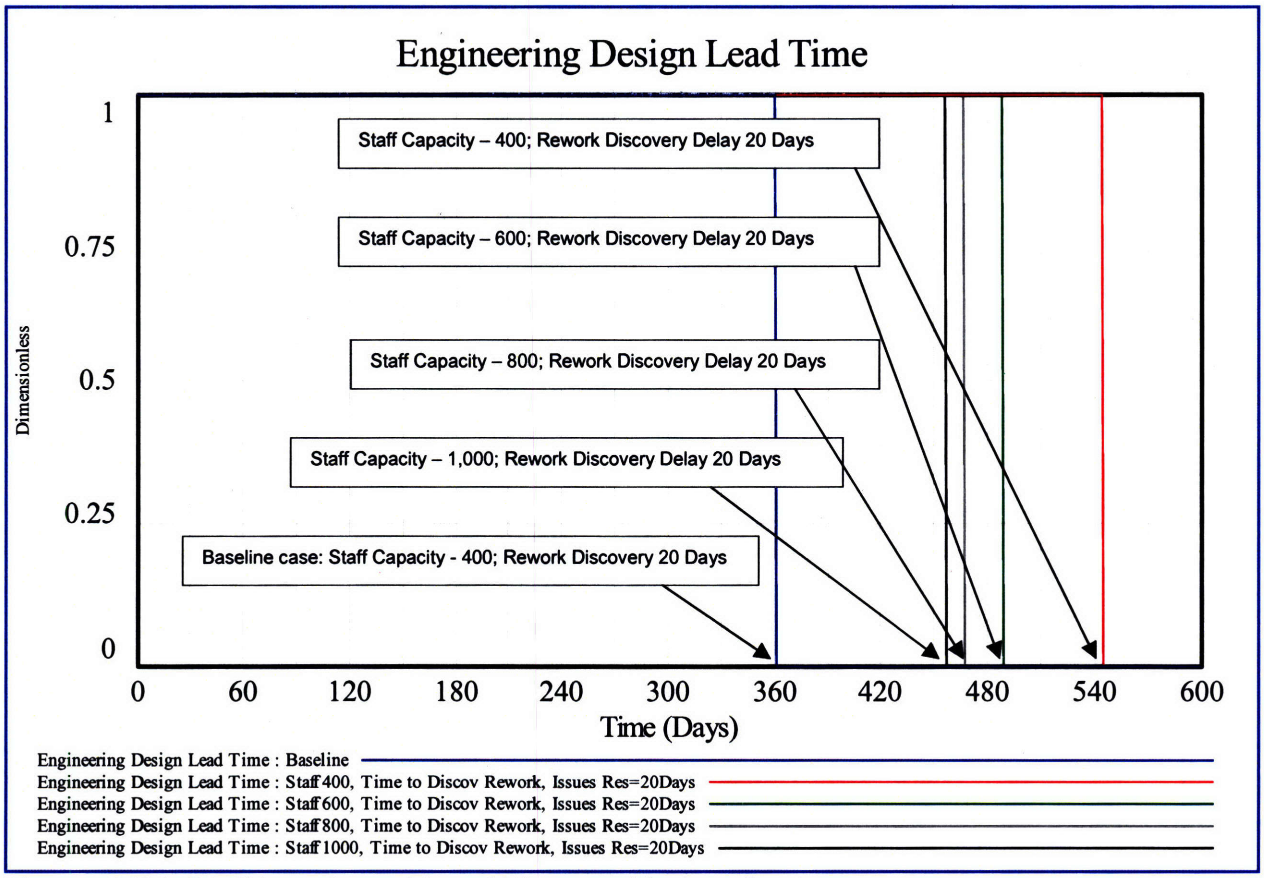


Figure 4.57: Staff Levels and Lead Time and Labor Cost

The reason is that the amount of design rework being generated is proportional to the staff capacity. As shown in figure 4.58, the amount of rework generated increases as the staff capacity increases. This results in higher cumulative work done with staff capacity increase as shown in figure 4.59.

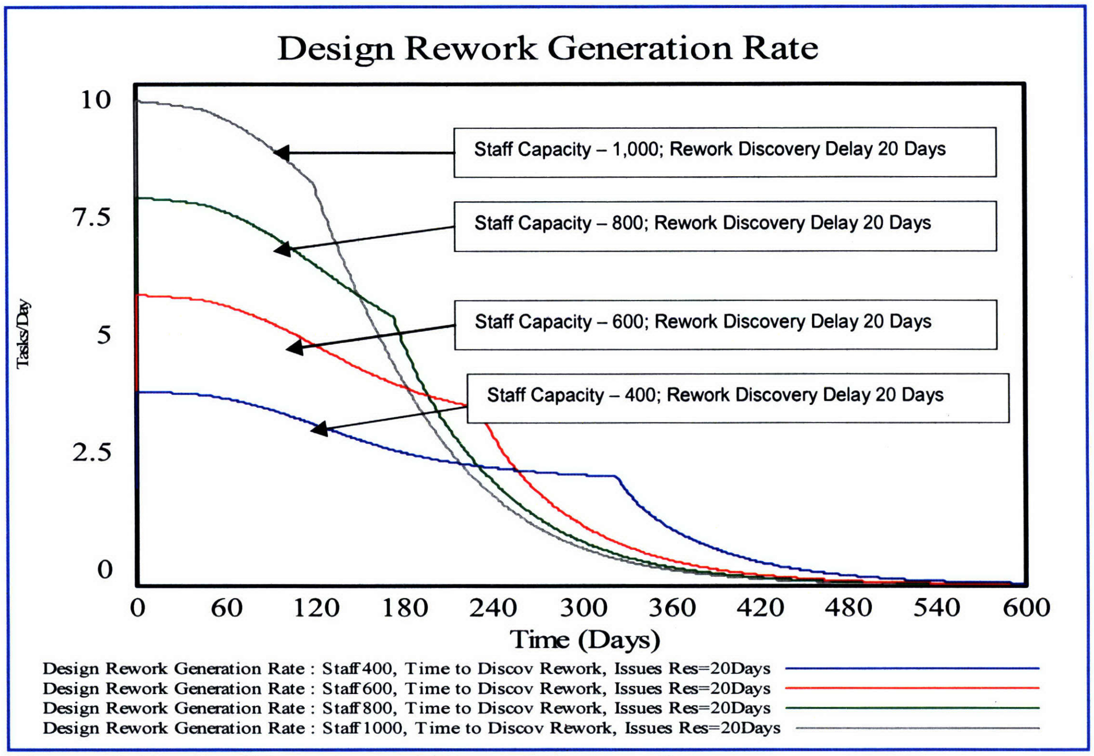


Figure 4.58: Staff Levels and Rework Generation

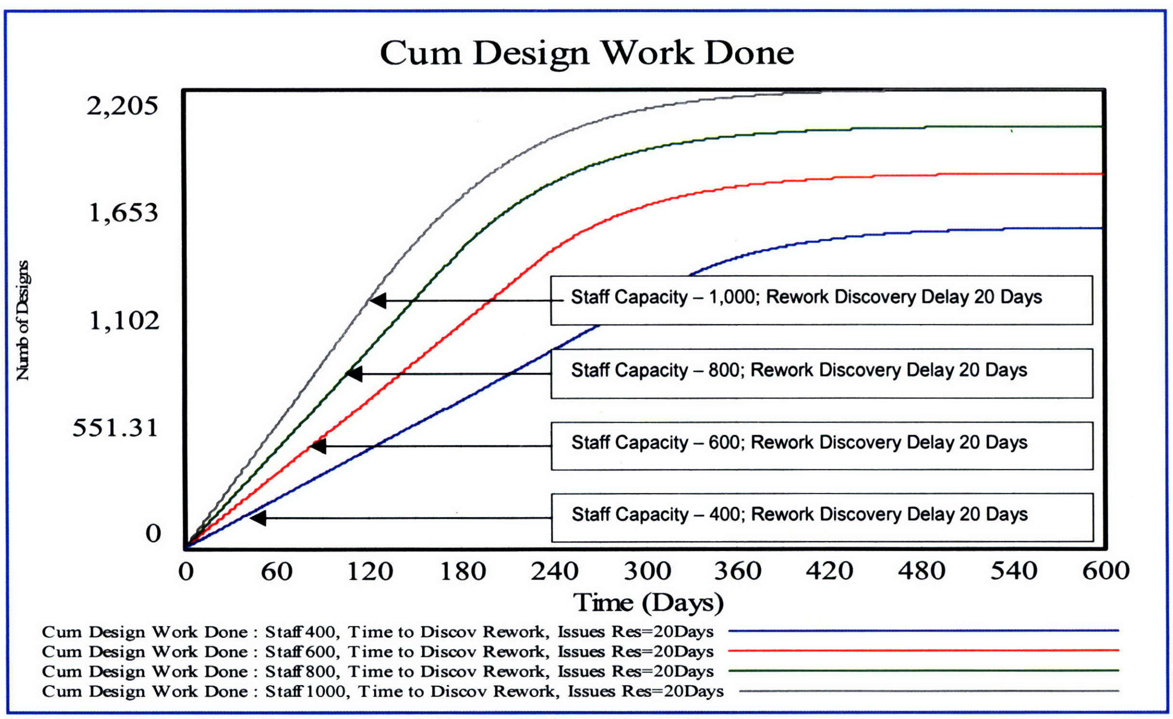


Figure 4.59: Staff Levels and Cumulative Work Done

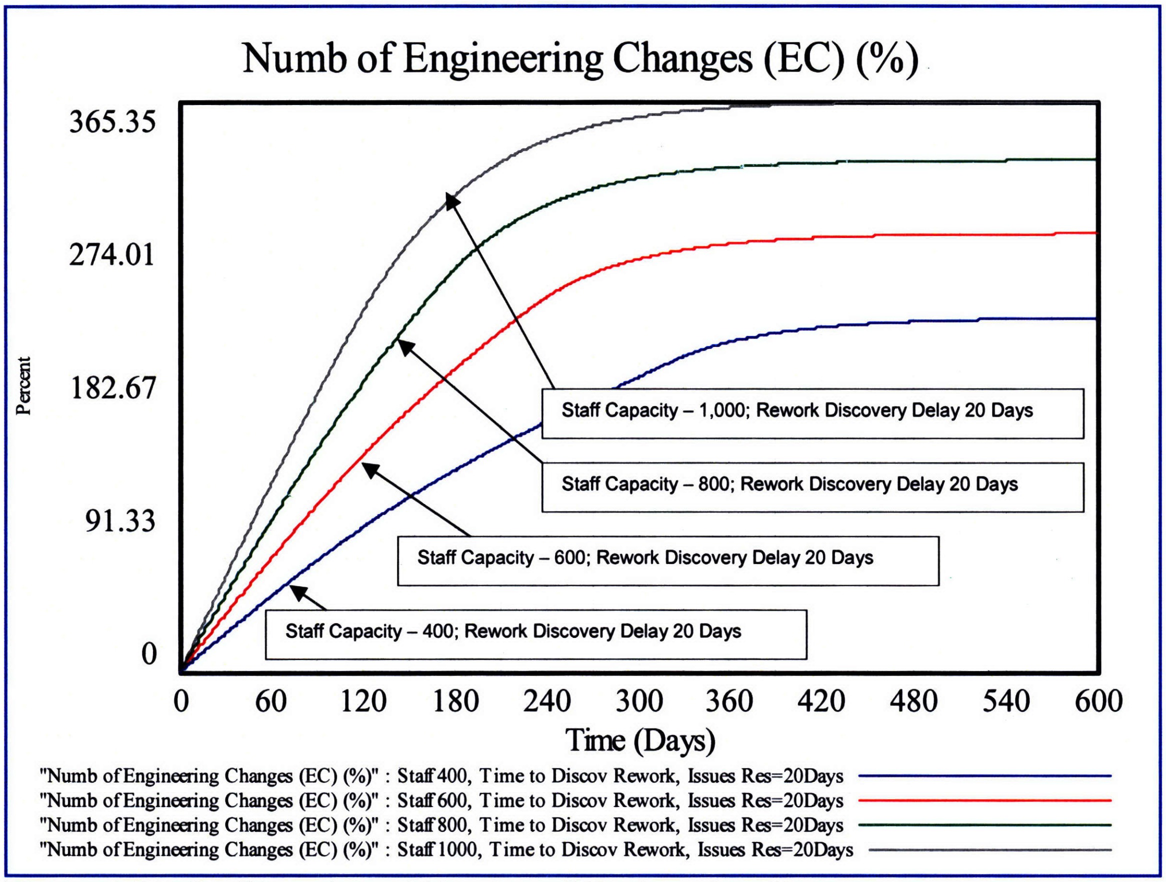


Figure 4.60: Staff Levels and Number of Engineering Changes

Figure 4.60 shows the corresponding numbers of Engineering Changes. For staff capacity of 400, 600, 800 and 1,000, the ECs = 226%, 280, 327 and 365 respectively. Figure 4.61 shows the corresponding Labor costs: for staff capacity of 400, 600, 800 and 1,000, the Labor costs are: $217,633; 293,350; 373,260 and 456,583 respectively.

Thus we see that even though staff capacity was increased 2.5 times the baseline staff capacity case, it was not possible to achieve the schedule baseline schedule of 360. The best Lead Time achieved was 457 days - with staff capacity of 1,000.

Again, figure 4.62, shows the Lead Time of 360 days for the Baseline case (*Mean-Time-to-Discover-Rework & Time-for-Issues-Resolution* = 5 days). Also shown are the Lead Times for staff capacities: 400, 600, 800 and 1,000 with (*Mean-Time-to-Discover-Rework & Time-for-Issues-Resolution* now decreased from 20 to 10 days). The Lead Times are: staff capacity of 400 - 421 days; staff capacity of 600 - 362 days; staff capacity of 800 - 336 days; staff capacity of 1,000 - 323 days.

We now see that with a staff capacity of 600 it is possible to meet the baseline Lead Time of 360 days.

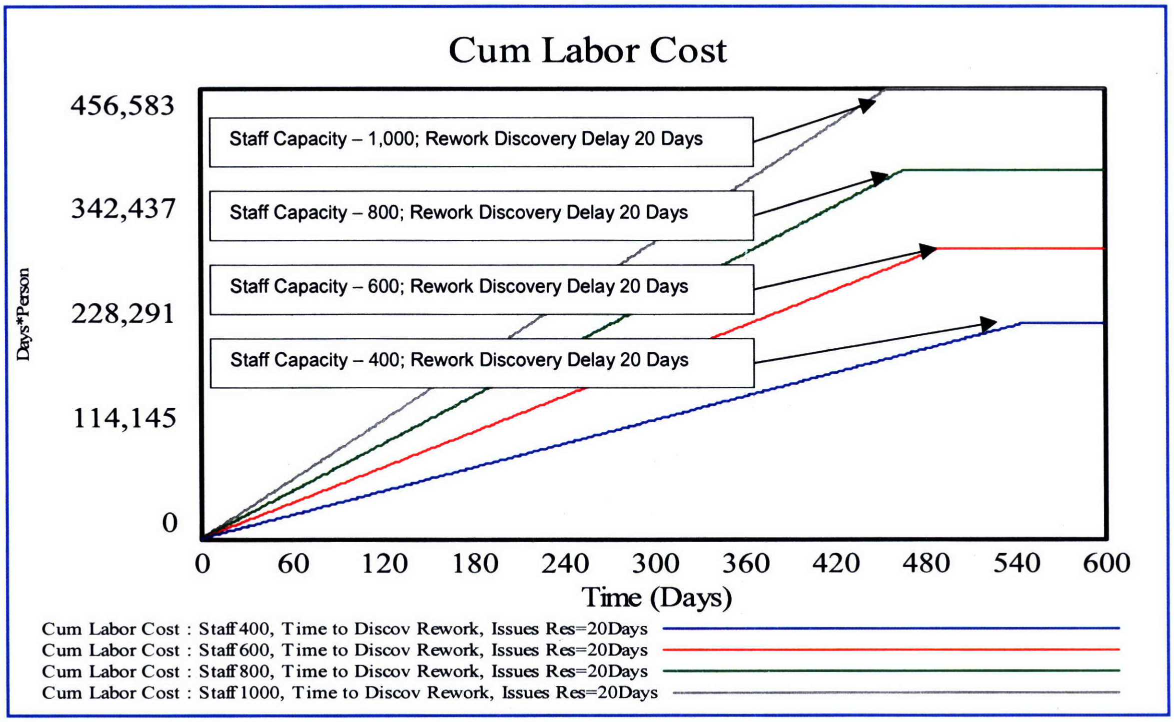


Figure 4.61: Staff Levels and Labor Cost

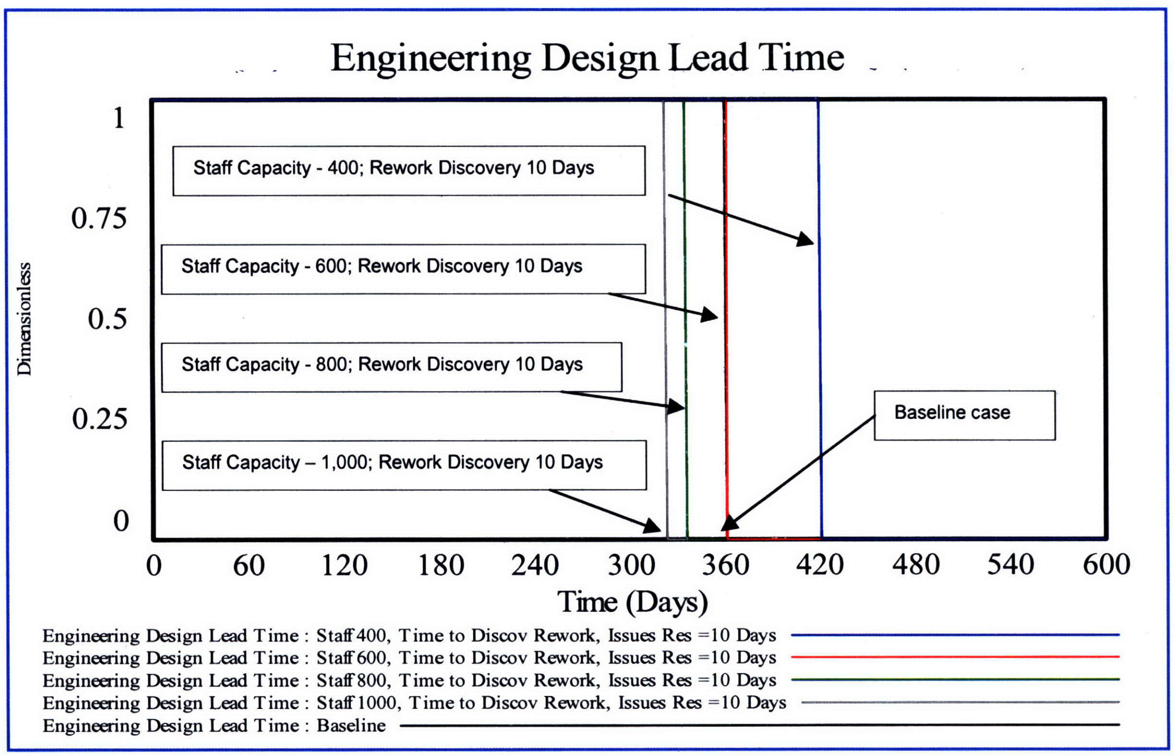


Figure 4.62: Staff Levels and Lead Time

Figure 4.63 shows the corresponding numbers of Engineering Changes for the case when *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* = 10 days. For staff capacity of 400, 600, 800 and 1,000, the ECs = 165%, 196, 224 and 3250 respectively. Figure 4.64 shows the corresponding Labor costs: for staff capacity of 400, 600, 800 and

1,000, the Labor costs are: $168,167; 216,850; 268,467 and 322,417 respectively. We see that if *Mean-Time-to-Discover-Rework* & *Time-for-Issues*-Resolution is not adequately controlled, the OEM will be very surprised at the inability of the supplier to accomplish the work on schedule – even though the supplier has no staff capacity constraints

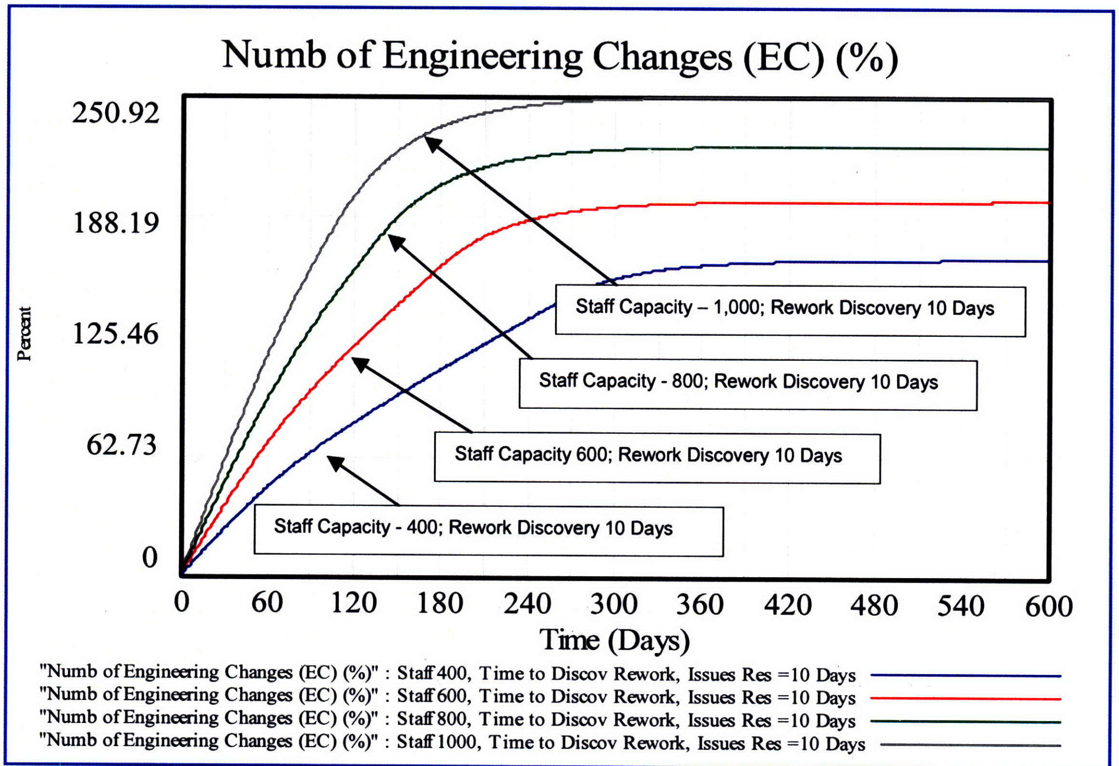


Figure 4.63: Staff Levels and EC

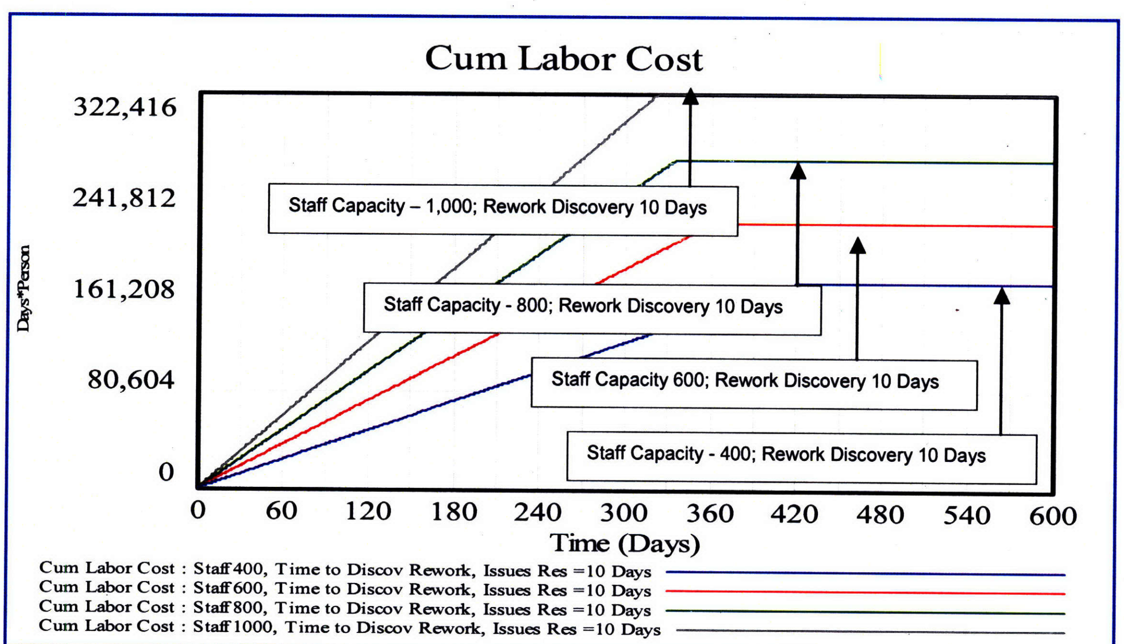


Figure 4.64: Staff Levels and Labor Cost

5. The Dynamics of Sourcing Engineering Design

5.1. Introduction

In the last chapter, we investigated the impact of various factors in the generation of rework or Engineering Change. As we saw, rework has a profound effect on *Engineering-Design-Lead-Time* and *Labor-Cost*. That analysis was more generalized. In this chapter, in order to develop strategies for sourcing Engineering Design work, we simulate scenarios with specific Supplier Staff Capacity, Quality and Labor costs. We simulate the model to investigate the dynamics of *Engineering-Design-Lead-Time* and *Labor-cost* of these exogenous variables for both In-House sourcing and Outsourcing:

1. *Mean-Time-to-Discover-Rework*
2. *Time-for-Issues-Resolution*
3. *Supplier-Quality*,
4. *Design-Complexity*
5. *Staff Capacity*
6. *Supplier Staff Capacity*
7. *Initial Number of Designs (Design-Volume)*

The scenarios for the sourcing of Engineering Design are developed under the six cases listed below.

- **Sourcing of Engineering Design Case 1**: Impact of *Quality* and *Mean-Time-to-Discover-Rework* + *Issues-Resolution* on *Engineering-Design-Lead-Time* and *Labor-Cost* (Simulations 1 & 2 in Table 5.1)

- **Sourcing of Engineering Design Case 2**: Impact of *Quality*, *Mean-Time-to-Discover-Rework* + *Issues-Resolution* and *Design-Volume* on *Engineering-Design-Lead-Time* and *Labor-Cost* (Simulations 3 & 4 in Table 5.1)

- **Sourcing of Engineering Design Case 3**: Impact of *Quality, Mean-Time-to-Discover-Rework* + *Issues-Resolution* & *Design-Complexity* on *Engineering-Design-Lead-Time* and *Labor-Cost* (Simulations 5 & 6 in Table 5.1)

- **Sourcing of Engineering Design Case 4**: Impact of *Quality, Mean-Time-to-Discover-Rework* + *Issues-Resolution* & *Design-Complexity* & *Design-Volume* on *Engineering-Design-Lead-Time* and *Labor-Cost.* (Simulations 7 & 8 in Table 5.1)

- **Sourcing of Engineering Design Case 5:** Impact of High Supplier *Quality* (60%), *Mean-Time-to-Discover-Rework* + *Issues-Resolution* on *Engineering Design Lead Time* and *Labor Cost* (Simulations 9 & 10 in Table 5.1)

- **Sourcing of Engineering Design Case 6**: Impact of Low Supplier *Quality* (40%), *Mean-Time-to-Discover-Rework* + *Issues-Resolution* on *Engineering Design Lead Time* and *Labor Cost* (Simulations 11 & 12 in Table 5.1)

Table 5.1: Simulation Plan

Simulations	Volume (# of Designs)	Design Complexity	Outsource Mean Time to Discover Rework + Issue Resolution (Days)	In-source Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Labor Cost: Normal/Low Cost Region
Simulation-1	474 x 1	1	20	5	52%	100% / 50%
Simulation-2	474 x 1	1	10	5	52%	100% / 50%
Simulation-3	474 x 2 = 948	1	20	5	52%	100% / 50%
Simulation-4	475 x 2 = 948	1	10	5	52%	100% / 50%
Simulation-5	474 x 1	2	20	5	52%	100% / 50%
Simulation-6	474 x 1	2	10	5	52%	100% / 50%
Simulation-7	475 x 2 = 948	2	20	5	52%	100% / 50%
Simulation-8	475 x 2 = 948	2	10	5	52%	100% / 50%
Simulation-9	474 x 1	1	20	5	60%	100% / 50%
Simulation-10	474 x 1	1	10	5	60%	100% / 50%
Simulation-11	474 x 1	1	20	5	40%	100% / 50%
Simulation-12	474 x 1	1	10	5	40%	100% / 50%

In chapter 2, we discussed some strategic reasons that OEMs outsource manufacturing. Some of the reasons that a company may decide to outsource its design work include:

- Capacity constraints – when the company does not have enough engineers to complete the designs on schedule if it were to undertake the design work in-house.
- The company does not have the requisite technological capability to perform the design in-house
- Cost reduction – the company can have a Suppler perform the design work at a lower cost than can be achieved in-house.

In chapter 4, analysis was presented for the cases:

- Hiring
- Over Time work
- Hiring & Over Time work.

In the current chapter, the analysis looks at options for sourcing of Engineering Design work. In order to investigate the impact of EC on Engineering Design Lead Times and Labor costs, the model employs a number of factors which impact the generation of EC as exogenous variable to study the dynamics of EC on Lead Times and Labor cost. These factors include: Quality, Design Complexity, Time to Discover Rework, Time for Issues Resolution, Hiring new and less experienced staff and Overtime work.

To enable an OEM make a sound judgment when faced with capacity constraint, we employ the model to analyze an example case in which an OEM faced with a staff capacity constraint because it has only 50% of the staff needed to finish the Engineering Design work explored its options as follows:

- Adopt an Overtime Strategy
- Adopt a Hiring Strategy

- Adopt a combination of Over Time and Hiring Strategy
- Adopt an Outsourcing Strategy

5.2. Scenarios Analysis

It is assumed that an OEM is faced with a staff capacity constraint because it has only 50% of the staff needed to finish the Engineering Design work in the Baseline case discussed above and defined by the following data:.

Definition of Baseline: This is the reference case in which the model is simulated with capacity of 400 fully experienced staff, with a Quality value of 52%, and a *Mean-Time-to-Discover-Rework* + *Issues-Resolution* of 5 Days.

Labor Rates: In this analysis, the Labor Rate is assumed to be identical for both In-sourcing and Outsourcing when the OEM and the supplier are in the same geographical area. **We assumed the rate to be $1 per Person-Day**.

Base on this Labor rate, the *Engineering Design Lead Time* = 360 days and *Labor Cost* = $144,158 for the Baseline case

We assumed the rate to be 50% (= .5x$1) per Person-Day when the OEM outsources to a Low-cost country such as India or China

The company therefore explores its options as follows:

5.2.1. Adopt an Over Time Strategy

Under the Over Time strategy, in addition to their regular work time, 50% percentage of the staff also do Over Time work. If, for example the company starts with a 50% of staff needed for the design work, and 50% of those staff are also on Over Time, then the company achieves 75% of the required staff level.

Main Drawbacks: Over Time work has negative impacts on both *Productivity* and *Quality*. As time progresses, the *Productivity* and *Quality* of work of Over Time staff decreases because they become tired – making them less productive; and less concentrated making their work more error-prone – which leads to decreased work quality.

5.2.2. Adopt a Hiring Strategy

Under the Hiring strategy, the company hires new staff to make up the staff short fall.

Main Drawbacks: Firstly, it takes some time to get the new hires on board. Secondly, and more importantly, new hires typically work only at a fraction of the *Productivity* and *Quality* of work of Experienced staff. These new Hires need training to bring them to the level of experienced staff – in terms of *Productivity* and *Quality*. How soon the new Hires become experienced would depend among other things on how aggressive the training program is. However, hiring solves capacity constraint problem much better than Over Time work.

5.2.3. Adopt a combination of Over Time and Hiring Strategy

A combination of Over Time and Hiring will have the problems associate with both strategies.

5.2.4. Adopt an Outsourcing Strategy

In this chapter we develop the Outsourcing part of the analysis. We assume that the OEM and the Supplier are at different locations – that is not co-located. The immediate impact of this fact is that it increases *Mean-Time-to-Discover-Rework.* There are three basic types of technical communications among the Design Engineers. These include communications for: **Coordination, Information and Inspiration.**

The benefits of clustering (co-location) OEM and supplier is that all three types of communication are enhanced. On the other hand, when the OEM and supplier are distributed (Non-co-located – as assumed here for the OEM and its Supplier), all three types of communications fall off sharply. Figure 5.1 shows the result of a study to determine the Probability of Communication as a function of Distance by Prof Tomas J. Allen of MIT Sloan School of Management [31, 32]. We see from the graph that Communications fall off sharply with distance. Insufficient levels of Communications due to physical separation between an OEM and its supplier is the major problem when the supplier is engaged in design work for the OEM because design is an iterative process requiring frequent communications between the design teams.

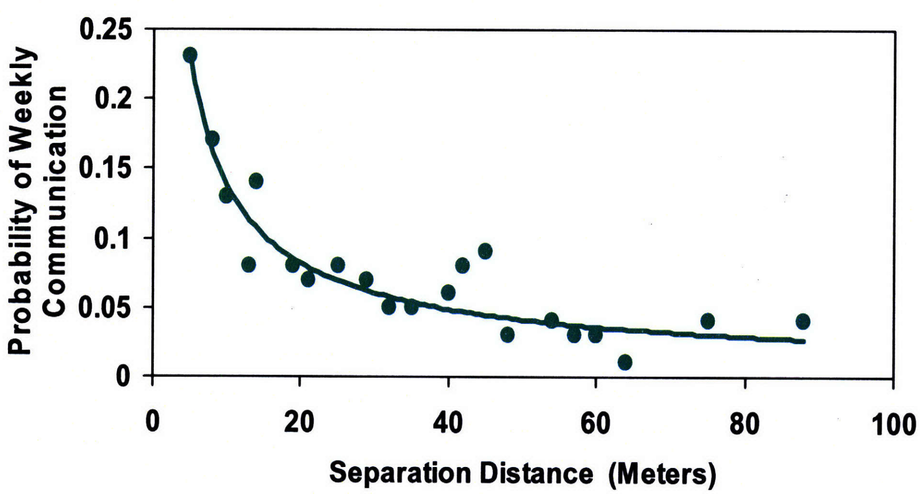


Figure 5.1. Probability of Technical Communication as a Function of Distance between Work Stations
Source: Prof Allen, T.J, MIT

Prof Allen's team also found that modern media: E-mail, Telephone, Video conference, File sharing , etc are 'bandwidth limited', in more than the physical sense, and reached the conclusion that : *"It is very difficult to discuss a complex problem or an idea by e-mail or telephone."* This poses a major problem when design work is outsourced to a Supplier who is typically not co-located with the OEM. Also, even when defects or rework are discovered, the time to resolves the issues usually takes longer when between the OEM and a Supplier – who are separate legal entities. Issues resolution might in fact take much longer if the Supplier somehow believes that a Design Change request in fact amounts to a Contract Change.

5.3. Sourcing of Engineering Design Case 1: Impact of *Quality* and *Mean-Time-to-Discover-Rework* + *Issues-Resolution* on *Engineering-Design-Lead-Time* and *Labor-Cost*

Table 5.2a: Simulations 1 & 2

Simulations	Volume (# of Designs)	Design Complexity	Outsource Mean Time to Discover Rework + Issue Resolution (Days)	In-source Mean Time to Discover Rework + Issue Resolution (Days)	Quality
Simulation-1	474 x 1	1	20	5	52%
Simulation-2	474 x 1	1	10	5	52%

Table 5.2a shows the values of the simulation variables. In this analysis only 50% of the required staff capacity is available In-House, or 200 staff (= 400*50%). The additional required staff can then be made up by In-House options – Hiring, Over Time, and a combination of Hiring and Over Time that the OEM can explore as shown in Table 5.2b. The dynamics of Hiring and Over Time have been discussed in great detail in the foregoing.
The Outsourcing options shown in Table 5.2b address the capacity constraints. The OEM has the option to choose from suppliers with staff capacities of between 400 to 1,000. In the simulations results shown, the In-House and Outsource options are assumed to have a *Mean-Time-to-Discover-Rework* + *Issues-Resolution* of 5 Days and 20 Days respectively.

In Table 5.2c, the In-House *Mean-Time-to-Discover-Rework* + *Issues-Resolution* remains unchanged at 5 Days, while the *Mean-Time-to-Discover-Rework* + *Issues-Resolution* for the Outsource options is decreased from 20 to 10 Days.

The chart of Figure 5.2a shows the results for the *Engineering-Design-Lead-Time* for:

- Simulation 1 : *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days and
- Simulation 2 : *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days

The chart of Figure 5.2b shows the results for the *Labor-Cost -Time* for:

- Simulation 1: *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days and
- Simulation 2: *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days

Table 5.2b: Simulation 1

Simulation 1	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days)	Lead Time Normalized to Baseline	Labor Cost	Labor Cost Normalized to Baseline
Baseline	**400**	**474 x 1**	**1**	**5**	**52%**	**360**	**100%**	**$ 144,158**	**100%**
In-House- Hiring	400	474 x 1	1	5	52%	404	112%	$ 157,433	109%
In-House - Over Time	300	474 x 1	1	5	52%	476	132%	$ 142,525	99%
In-House -Hiring +Over Time	400	474 x 1	1	5	52%	409	114%	$ 161,567	112%
Outsource	400	474 x 1	1	20	52%	544	151%	$ 217,608	151%
Outsource	500	474 x 1	1	20	52%	509	141%	$ 254,925	177%
Outsource	600	474 x 1	1	20	52%	488	136%	$ 293,388	204%
Outsource	700	474 x 1	1	20	52%	475	132%	$ 332,923	231%
Outsource	800	474 x 1	1	20	52%	466	129%	$ 373,383	259%
Outsource	900	474 x 1	1	20	52%	460	128%	$ 414,656	288%
Outsource	1000	474 x 1	1	20	52%	456	127%	$ 456,646	317%

Table 5.2c: Simulation 2

Simulation 2	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days)	Lead Time Normalized to Baseline	Labor Cost	Labor Cost Normalized to Baseline
Baseline	**400**	**474 x 1**	**1**	**5**	**52%**	**360**	**100%**	**$ 144,158**	**100%**
In-House- Hiring	400	474 x 1	1	5	52%	404	112%	$ 157,433	109%
In-House - Over Time	300	474 x 1	1	5	52%	476	132%	$ 142,525	99%
In-House -Hiring +Over Time	400	474 x 1	1	5	52%	409	114%	$ 161,567	112%
Outsource	400	474 x 1	1	10	52%	420	117%	$ 168,000	117%
Outsource	500	474 x 1	1	10	52%	384	107%	$ 192,000	133%
Outsource	600	474 x 1	1	10	52%	361	100%	$ 216,600	150%
Outsource	700	474 x 1	1	10	52%	346	96%	$ 242,200	168%
Outsource	800	474 x 1	1	10	52%	335	93%	$ 268,000	186%
Outsource	900	474 x 1	1	10	52%	327	91%	$ 294,300	204%
Outsource	1000	474 x 1	1	10	52%	322	89%	$ 322,000	223%

Figure 5.2a: Variation of Engineering Design Lead Time for In-Hourse & Outsource Options
(Simulations 1 & 2: Initial # of Designs = 474; Design Complexity = 1)

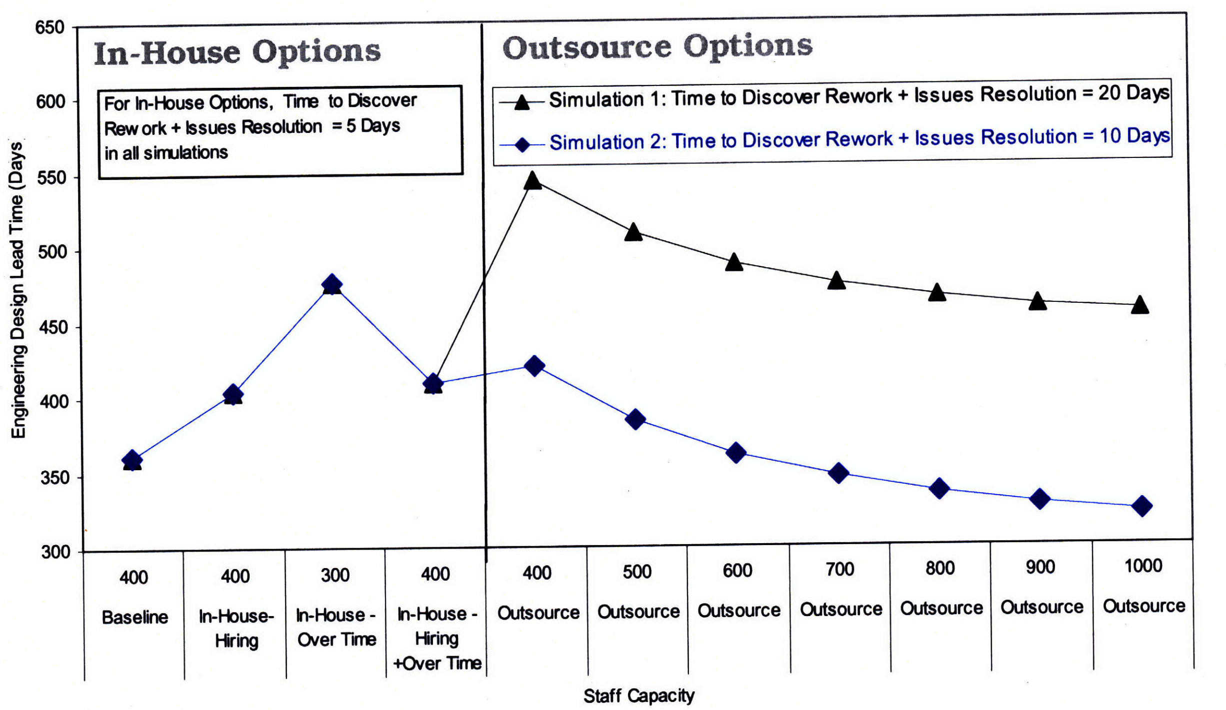
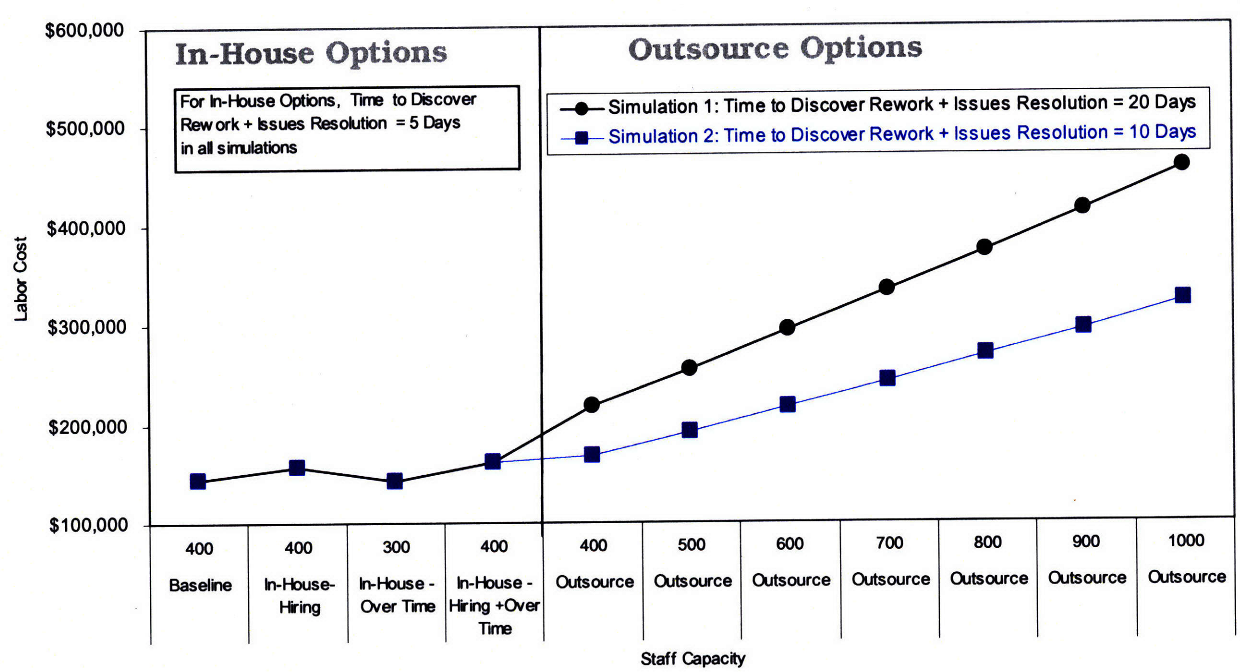


Figure 5.2b: Variation of Labor Cost for In-Hourse & Outsource Options
(Simulations 1 & 2: Initial # of Designs = 474; Design Complexity = 1)



To determine the best option to source the design work in this case, the OEM may first decide that either cost or schedule consideration is the more important factor driving its decision. Since cost would almost surely rank as a key factor in all decision making, let us then assume first that cost is the more important factor here than schedule. We see from the chart of figure 5.2b for labor cost that the In-House Over Time option with cost of $142,525 meets and even marginally exceeds the Baseline cost target of $144,158. However, from the figure 5.2a for lead time that Over Time option lags the Baseline schedule target of 360 days by as much as 32%. The OEM may want to strike a better balance between cost and schedule in which case the Hiring and the combination of Hiring and Over Time are the ideal options since they are only about 9 to 14% above the Baseline cost and schedule targets.

To analyze the Outsourcing options, we first look at the Lead Time and Labor cost curves for *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days. As can be seen from the graphs of figures 5.2a & b, the Outsourcing options are not at all competitive in this case.

It is assumed that the OEM can works more collaboratively with the suppliers, such that the *Mean-Time-to-Discover-Rework* + *Issues-Resolution* for the Outsourcing options decrease from 20 to 10 Days as shown in Table 5.2c. The curves for *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days of Figures 5.2a & b show the new dynamics. If cost is the more important factor, then the In-House options are still better. However, if schedule is a critical factor, then we see that the supplier with the staff capacity of 600 or more will meet the Baseline target of 360 Days, but at a cost that exceeds target by 50%. However, from figure 5.2a, we see that outsourcing can reduce Lead Time significantly because of the supplier's ability to deploy more staff capacity. Thus, as the supplier increases staff capacity, Lead Time decreases – but Labor cost also increases correspondingly.

5.4. Sourcing of Engineering Design Case 2: Impact of *Quality, Mean-Time-to-Discover-Rework + Issues-Resolution* and *Design-Volume* on *Engineering-Design-Lead-Time* and *Labor-Cost*

Table 5.3a: Simulations 3 & 4

Simulations	Volume (# of Designs)	Design Complexity	Outsource Mean Time to Discover Rework + Issue Resolution (Days)	In-source Mean Time to Discover Rework + Issue Resolution (Days)	Quality
Simulation-3	474 x 2 = 948	1	20	5	52%
Simulation-4	475 x 2 = 948	1	10	5	52%

For this analysis, the *Initial Number of Designs* is doubled from 474 to 948 to set Design Volume (# of Design) = 474x2; and the *Design-Complexity* = 1, and simulate the impact on *Engineering-Design-Lead-Time and Labor-Cost.* As in the analysis in preceding section, only 50% of the require staff capacity is available In-House, or 200 staff. The additional required staff is then be made up by In-House options – Hiring, Over Time, and a combination of Hiring and Over Time that the OEM can explore as shown in Table 5.3. The OEM has the option to choose from suppliers with staff capacities between 400 to 1,000. In the simulations results shown in Table 5.3b, the In-House and Outsource options are assumed to have a *Mean-Time-to-Discover-Rework + Issues-Resolution* of 5 Days and 20 Days respectively. In Table 5.3c, the In-House *Mean-Time-to-Discover-Rework + Issues-Resolution* remains unchanged at 5 Days, while the *Mean-Time-to-Discover-Rework + Issues-Resolution* for the Outsource options is decreased from 20 to 10 Days.

The chart of Figure 5.3a shows the results for the *Engineering-Design-Lead-Time* for:

- Simulation 3 : *Mean-Time-to-Discover-Rework + Issues-Resolution* = 20 Days and
- Simulation 4 : *Mean-Time-to-Discover-Rework + Issues-Resolution* = 10 Days

The chart of Figure 5.3b shows the results for the *Labor-Cost -Time* for:

- Simulation 3: *Mean-Time-to-Discover-Rework + Issues-Resolution* = 20 Days and
- Simulation 4: *Mean-Time-to-Discover-Rework + Issues-Resolution* = 10 Days

Table 5.3b:Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 20 Days

Simulation 3	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days)	Lead Time Normalized to Baseline	Labor Cost	Labor Cost Normalized to Baseline
Baseline	400	474 x 2	1	5	52%	562	100%	$ 224,433	100%
In-House- Hiring	400	474 x 2	1	5	52%	606	108%	$ 238,367	106%
In-House - Over Time	300	474 x 2	1	5	52%	866	154%	$ 259,525	116%
In-House -Hiring +Over Time	400	474 x 2	1	5	52%	658	117%	$ 260,833	116%
Outsource	400	474 x 2	1	20	52%	739	131%	$ 295,233	132%
Outsource	500	474 x 2	1	20	52%	658	117%	$ 328,792	146%
Outsource	600	474 x 2	1	20	52%	606	108%	$ 363,550	162%
Outsource	700	474 x 2	1	20	52%	570	101%	$ 398,942	178%
Outsource	800	474 x 2	1	20	52%	545	97%	$ 435,267	194%
Outsource	900	474 x 2	1	20	52%	525	93%	$ 472,125	210%
Outsource	1000	474 x 2	1	20	52%	510	91%	$ 509,917	227%

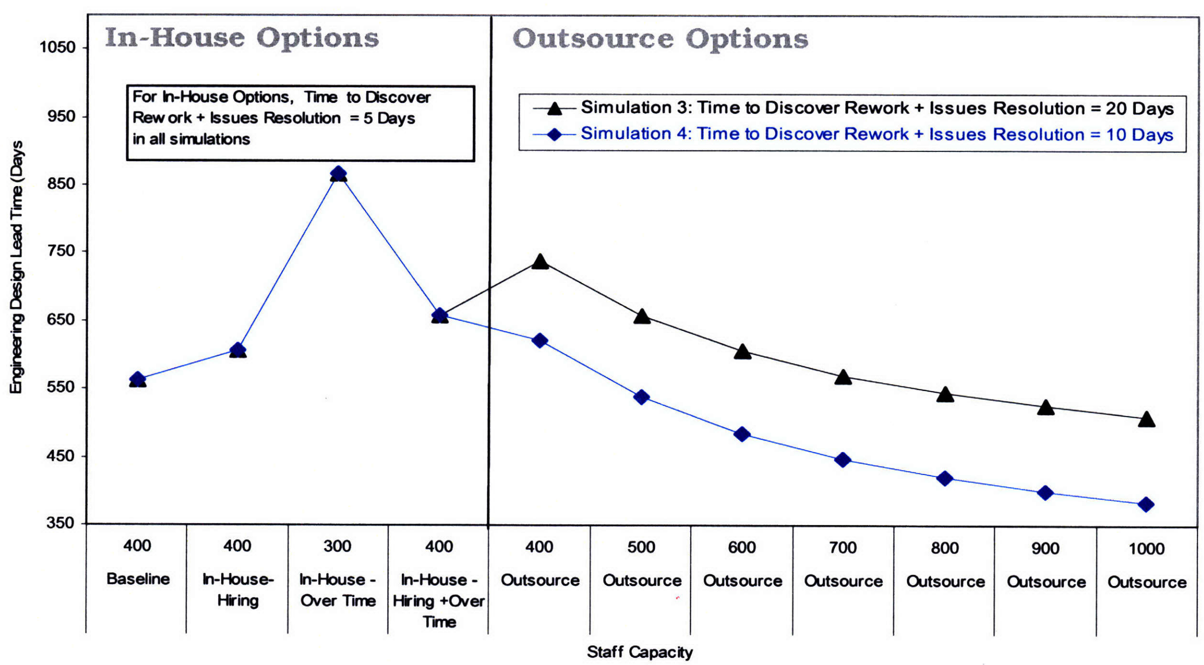
Table 5.3c:Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 10 Days

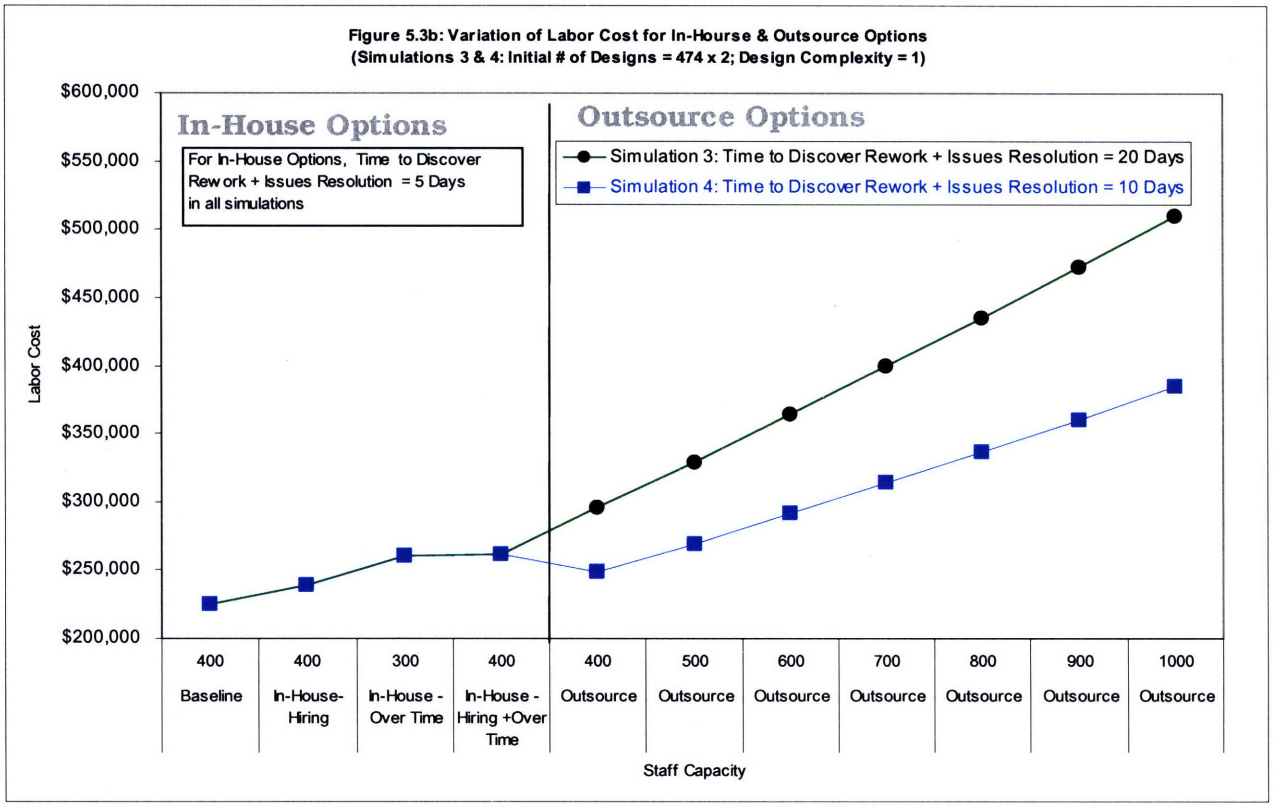
Simulation 4	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days)	Lead Time Normalized to Baseline	Engineering Design Cost	Cost Normalized to Baseline
Baseline	400	474 x 2	1	5	52%	562	100%	$ 224,433	100%
In-House- Hiring	400	474 x 2	1	5	52%	606	108%	$ 238,367	106%
In-House - Over Time	300	474 x 2	1	5	52%	866	154%	$ 259,525	116%
In-House -Hiring +Over Time	400	474 x 2	1	5	52%	658	117%	$ 260,833	116%
Outsource	400	474 x 2	1	10	52%	620	110%	$ 247,833	110%
Outsource	500	474 x 2	1	10	52%	538	96%	$ 268,792	120%
Outsource	600	474 x 2	1	10	52%	485	86%	$ 290,650	130%
Outsource	700	474 x 2	1	10	52%	448	80%	$ 313,192	140%
Outsource	800	474 x 2	1	10	52%	421	75%	$ 336,333	150%
Outsource	900	474 x 2	1	10	52%	400	71%	$ 359,925	160%
Outsource	1000	474 x 2	1	10	52%	384	68%	$ 383,917	171%

For Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days Table 5.3b, we see that the In-House Hiring option returns the best result in terms of *Engineering-Design-Lead-Time* and *Labor-Cost* which are 606 Days (8% over the Baseline target), and $238,367 (6% over the Baseline target) respectively. Note that Outsourcing will require a supplier with 700 staff capacity to meet the Baseline *Engineering-Design-Lead-Time* target – but at a *Labor-Cost* that exceed the target by as much as 78%. Again, we see that Outsourcing is not a viable option in this case.

When Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* is reduced from 20 to 10 Days Table 5.3c, the Outsourcing options become quite competitive. We see that a supplier with a staff of 400 can achieve an *Engineering-Design-Lead-Time* and *Labor-Cost* of 620 Days (10% over the Baseline target), and $247,833 (10% over the Baseline target) respectively.

Figure 5.3a: Variation of Engineering Design Lead Time for In-Hourse & Outsource Options (Simulations 3 & 4: Initial # of Designs = 474 x 2; Design Complexity = 1)





5.5. Sourcing of Engineering Design Case 3: Impact of Quality, Mean-Time-to-Discover-Rework + Issues-Resolution & Design-Complexity on Engineering-Design-Lead-Time and Labor-Cost

Table 5.4a: Simulations 5 & 6

Simulations	Volume (# of Designs)	Design Complexity	Outsource Mean Time to Discover Rework + Issue Resolution (Days)	In-source Mean Time to Discover Rework + Issue Resolution (Days)	Quality
Simulation-5	474 x 1	2	20	5	52%
Simulation-6	474 x 1	2	10	5	52%

For this analysis, the *Initial Number of Designs* is 474 x 1, and *Design-Complexity* =2 to study the dynamics on *Engineering-Design-Lead-Time* and *Labor-Cost*. As in the analysis in preceding section, only 50% of the require staff capacity is available In-House, or 200 staff. The additional required staff is then be made up by In-House options – Hiring, Over Time, and a combination of Hiring and Over Time that the OEM can explore as shown in Tables 5.4a-c.

The OEM has the option to choose from suppliers with staff capacities of between 400 to 1,000. In the simulations results shown in Table 5.4b, the In-House and Outsource options are assumed to have a *Mean-Time-to-Discover-Rework* + *Issues-Resolution* of 5 Days and 20 Days respectively. In Table 5.4c, the In-House *Mean-Time-to-Discover-Rework* + *Issues-Resolution* remains unchanged at 5 Days, while the *Mean-Time-to-*

Discover-Rework + *Issues-Resolution* for the Outsource options is decreased from 20 to 10 Days.

The chart of Figure 5.4a shows the results for the *Engineering-Design-Lead-Time* for:

- Simulation 5 : *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days and
- Simulation 6 : *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days

The chart of Figure 5.4b shows the results for the *Labor-Cost -Time* for:

- Simulation 5: *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days and
- Simulation 6: *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days

Table 5.4b: Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 20 Days

Simulation 5	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days)	Lead Time Normalized to Baseline	Labor Cost	Labor Cost Normalized to Baseline
Baseline	**400**	**474 x 1**	**2**	**5**	**52%**	**419**	**100%**	**$ 167,433**	**100%**
In-House- Hiring	400	474 x 1	2	5	52%	461	110%	$ 180,233	108%
In-House - Over Time	300	474 x 1	2	5	52%	549	131%	$ 164,525	98%
In-House -Hiring +Over Time	400	474 x 1	2	5	52%	476	114%	$ 188,167	112%
Outsource	400	474 x 1	2	20	52%	769	184%	$ 307,367	184%
Outsource	500	474 x 1	2	20	52%	736	176%	$ 367,792	220%
Outsource	600	474 x 1	2	20	52%	717	171%	$ 429,650	257%
Outsource	700	474 x 1	2	20	52%	704	168%	$ 492,392	294%
Outsource	800	474 x 1	2	20	52%	696	166%	$ 556,333	332%
Outsource	900	474 x 1	2	20	52%	692	165%	$ 622,725	372%
Outsource	1000	474 x 1	2	20	52%	691	165%	$ 690,083	412%

Table 5.4c: Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 10 Days

Simulation 6	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days)	Lead Time Normalized to Baseline	Labor Cost	Labor Cost Normalized to Baseline
Baseline	**400**	**474 x 1**	**2**	**5**	**52%**	**419**	**100%**	**$ 167,433**	**100%**
In-House- Hiring	400	474 x 1	2	5	52%	461	110%	$ 180,233	108%
In-House - Over Time	300	474 x 1	2	5	52%	549	131%	$ 164,525	98%
In-House -Hiring +Over Time	400	474 x 1	2	5	52%	476	114%	$ 188,167	112%
Outsource	400	474 x 1	2	10	52%	535	128%	$ 213,633	128%
Outsource	500	474 x 1	2	10	52%	499	119%	$ 249,208	149%
Outsource	600	474 x 1	2	10	52%	477	114%	$ 285,650	171%
Outsource	700	474 x 1	2	10	52%	462	110%	$ 322,992	193%
Outsource	800	474 x 1	2	10	52%	452	108%	$ 361,133	216%
Outsource	900	474 x 1	2	10	52%	445	106%	$ 399,975	239%
Outsource	1000	474 x 1	2	10	52%	440	105%	$ 439,083	262%

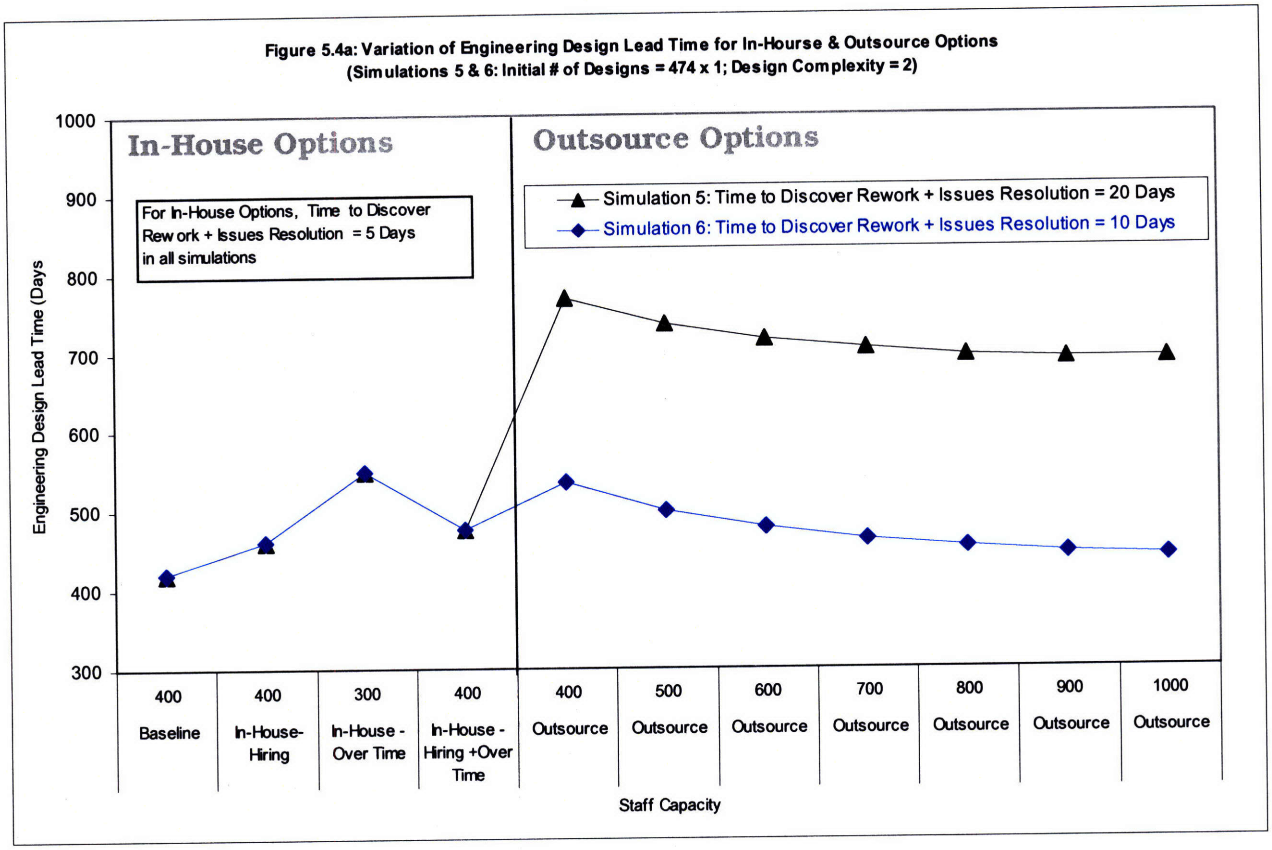


Figure 5.4a: Variation of Engineering Design Lead Time for In-Hourse & Outsource Options
(Simulations 5 & 6: Initial # of Designs = 474 x 1; Design Complexity = 2)
In-House Options
Outsource Options
For In-House Options, Time to Discover Rework + Issues Resolution = 5 Days in all simulations
Simulation 5: Time to Discover Rework + Issues Resolution = 20 Days
Simulation 6: Time to Discover Rework + Issues Resolution = 10 Days
Engineering Design Lead Time (Days
1000
900
800
700
600
500
400
300
400 Baseline
400 In-House-Hiring
300 In-House - Over Time
400 In-House - Hiring +Over Time
400 Outsource
500 Outsource
600 Outsource
700 Outsource
800 Outsource
900 Outsource
1000 Outsource
Staff Capacity

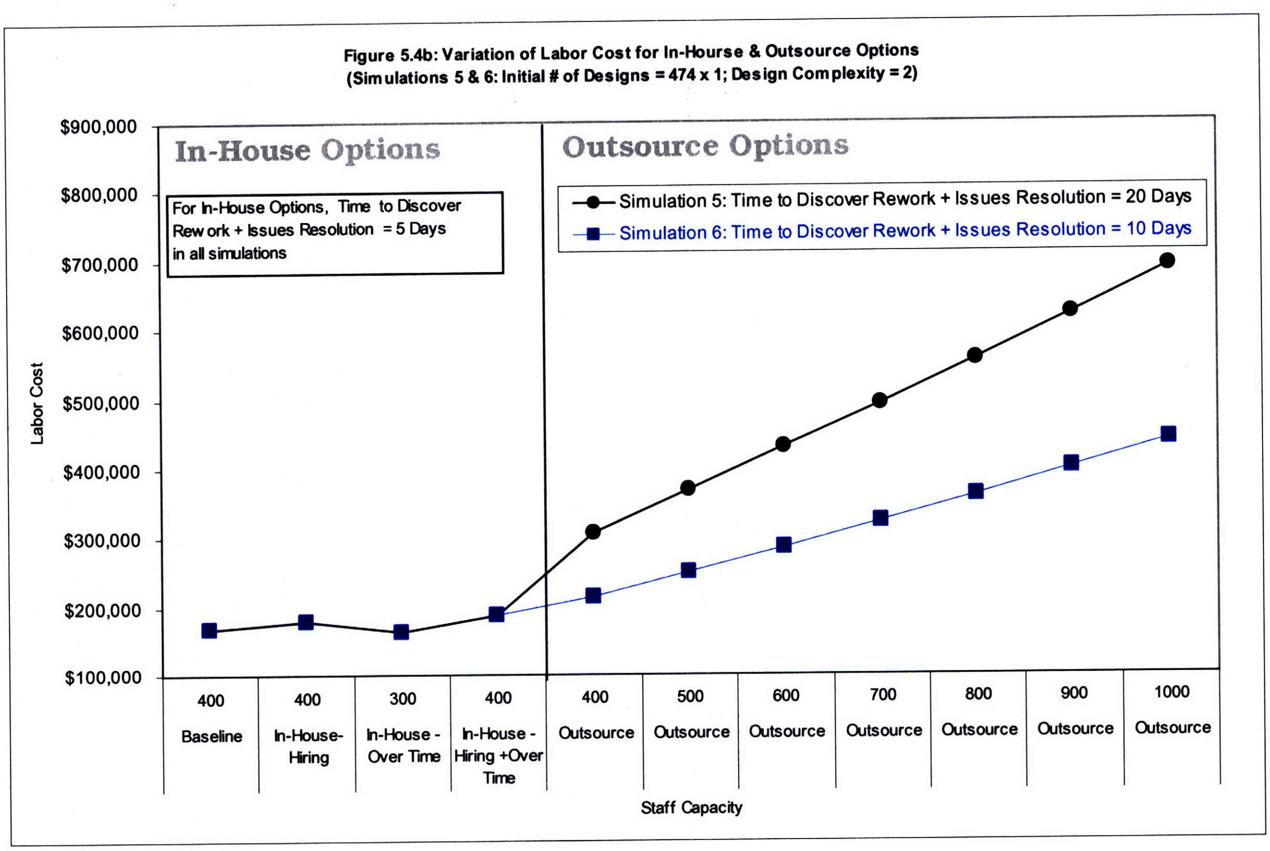


Figure 5.4b: Variation of Labor Cost for In-Hourse & Outsource Options
(Simulations 5 & 6: Initial # of Designs = 474 x 1; Design Complexity = 2)
In-House Options
Outsource Options
For In-House Options, Time to Discover Rework + Issues Resolution = 5 Days in all simulations
Simulation 5: Time to Discover Rework + Issues Resolution = 20 Days
Simulation 6: Time to Discover Rework + Issues Resolution = 10 Days
Labor Cost
$900,000
$800,000
$700,000
$600,000
$500,000
$400,000
$300,000
$200,000
$100,000
400 Baseline
400 In-House-Hiring
300 In-House - Over Time
400 In-House - Hiring +Over Time
400 Outsource
500 Outsource
600 Outsource
700 Outsource
800 Outsource
900 Outsource
1000 Outsource
Staff Capacity

For Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days Table 5.4b, we see that the In-House Hiring option returns the best result in terms of *Engineering-Design-Lead-Time* and *Labor-Cost* which are 461 Days (10% over the Baseline target), and $180,233 (8% over the Baseline target) respectively. Outsourcing is far too expensive in this case.

When Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* is reduced from 20 to 10 Days Table 5.4c, the Outsourcing options are still quite costly. For example, we see that a supplier with a staff of 700 can achieve an *Engineering-Design-Lead-Time* and *Labor-Cost* of 462 Days (10% over the Baseline target), but at a cost of $322,992 (93% over the Baseline target) respectively. So we see that as *Design-Complexity* increases, the more costly it becomes to outsource a design work.

5.6. Sourcing of Engineering Design Case 4: Impact of *Quality, Mean-Time-to-Discover-Rework + Issues-Resolution & Design-Complexity & Design-Volume* on *Engineering-Design-Lead-Time* and *Labor-Cost.*

Table 5.5a: Simulations 7 & 8

Simulations	Volume (# of Designs)	Design Complexity	Outsource Mean Time to Discover Rework + Issue Resolution (Days)	In-source Mean Time to Discover Rework + Issue Resolution (Days)	Quality
Simulation-7	475 x 2 = 948	2	20	5	52%
Simulation-8	475 x 2 = 948	2	10	5	52%

For this analysis, the *Initial Number of Designs* is 474 x 2, and *Design-Complexity* =2 to study the dynamics on *Engineering-Design-Lead-Time* and *Labor-Cost.* As in the analysis in preceding section, only 50% of the require staff capacity is available In-House, or 200 staff. The additional required staff is then be made up by In-House options – Hiring, Over Time, and a combination of Hiring and Over Time that the OEM can explore as shown in Tables 5.5a-c.

The OEM has the option to choose from suppliers with staff capacities between 400 to 1,000. In the simulations results shown in Table 5.5b, the In-House and Outsource options are assumed to have a *Mean-Time-to-Discover-Rework* + *Issues-Resolution* of 5 Days and 20 Days respectively. In Table 5.5c, the In-House *Mean-Time-to-Discover-Rework* + *Issues-Resolution* remains unchanged at 5 Days, while the *Mean-Time-to-Discover-Rework* + *Issues-Resolution* for the Outsource options is decreased from 20 to 10 Days.

The chart of Figure 5.5a shows the results for the *Engineering-Design-Lead-Time* for:

- Simulation 7 : *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days and
- Simulation 8 : *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days

The chart of Figure 5.5b shows the results for the *Labor-Cost -Time* for:

- Simulation 7: *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days and
- Simulation 8: *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days

Table 5.5b: Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 20 Days

Simulation 7	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days)	Lead Time Normalized to Baseline	Labor Cost	Labor Cost Normalized to Baseline
Baseline	400	474 x 2	2	5	52%	620	100%	$ 247,633	100%
In-House- Hiring	400	474 x 2	2	5	52%	662	107%	$ 260,633	105%
In-House - Over Time	300	474 x 2	2	5	52%	951	153%	$ 285,125	115%
In-House -Hiring +Over Time	400	474 x 2	2	5	52%	729	118%	$ 289,367	117%
Outsource	400	474 x 2	2	20	52%	959	155%	$ 383,433	155%
Outsource	500	474 x 2	2	20	52%	880	142%	$ 439,708	178%
Outsource	600	474 x 2	2	20	52%	829	134%	$ 497,050	201%
Outsource	700	474 x 2	2	20	52%	794	128%	$ 555,392	224%
Outsource	800	474 x 2	2	20	52%	769	124%	$ 614,733	248%
Outsource	900	474 x 2	2	20	52%	750	121%	$ 674,925	273%
Outsource	1000	474 x 2	2	20	52%	736	119%	$ 735,583	297%

Table 5.5c: Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 10 Days

Simulation 8	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days)	Lead Time Normalized to Baseline	Engineering Design Cost	Cost Normalized to Baseline
Baseline	400	474 x 2	2	5	52%	620	100%	$ 247,633	100%
In-House- Hiring	400	474 x 2	2	5	52%	662	107%	$ 260,633	105%
In-House - Over Time	300	474 x 2	2	5	52%	951	153%	$ 285,125	115%
In-House -Hiring +Over Time	400	474 x 2	2	5	52%	729	118%	$ 289,367	117%
Outsource	400	474 x 2	2	10	52%	732	118%	$ 292,767	118%
Outsource	500	474 x 2	2	10	52%	651	105%	$ 325,208	131%
Outsource	600	474 x 2	2	10	52%	598	96%	$ 358,550	145%
Outsource	700	474 x 2	2	10	52%	561	90%	$ 392,642	159%
Outsource	800	474 x 2	2	10	52%	535	86%	$ 427,267	173%
Outsource	900	474 x 2	2	10	52%	514	83%	$ 462,525	187%
Outsource	1000	474 x 2	2	10	52%	499	80%	$ 498,417	201%

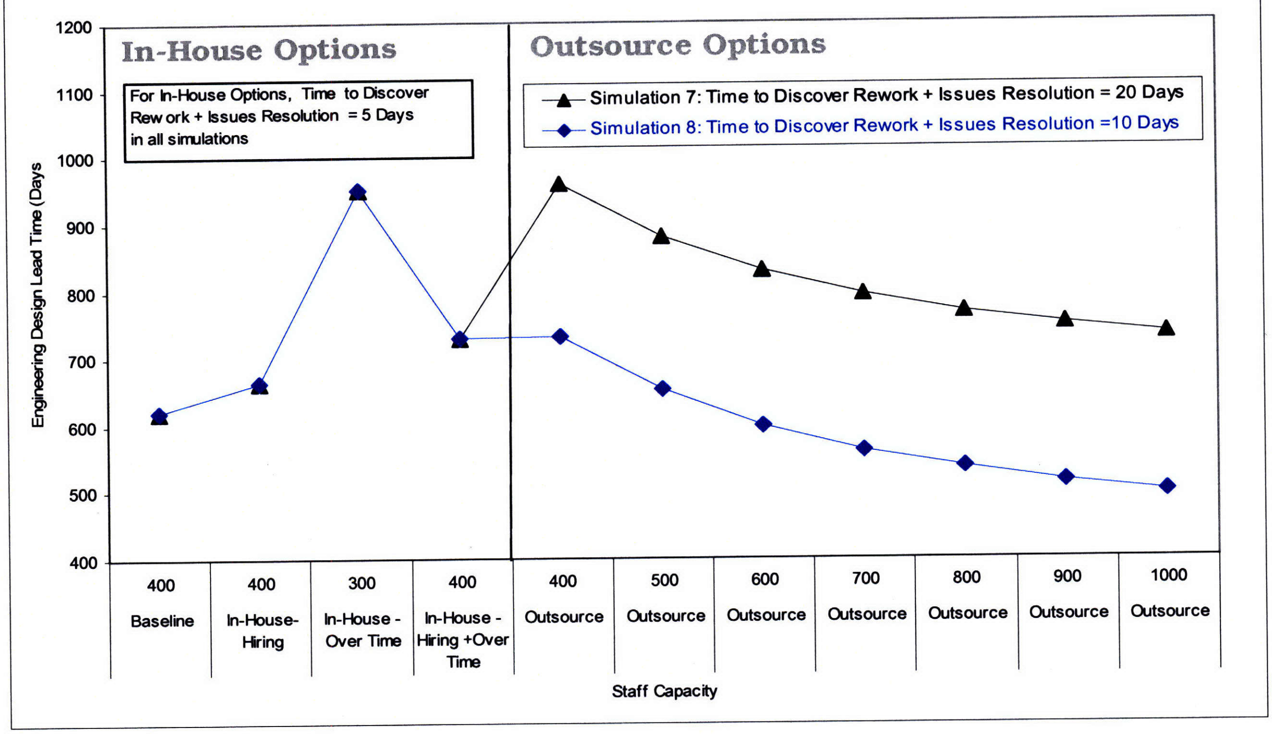


Figure 5.5a: Variation of Engineering Design Lead Time for In-Hourse & Outsource Options
(Simulations7 & 8: Initial # of Designs = 474 x 2; Design Complexity = 2)

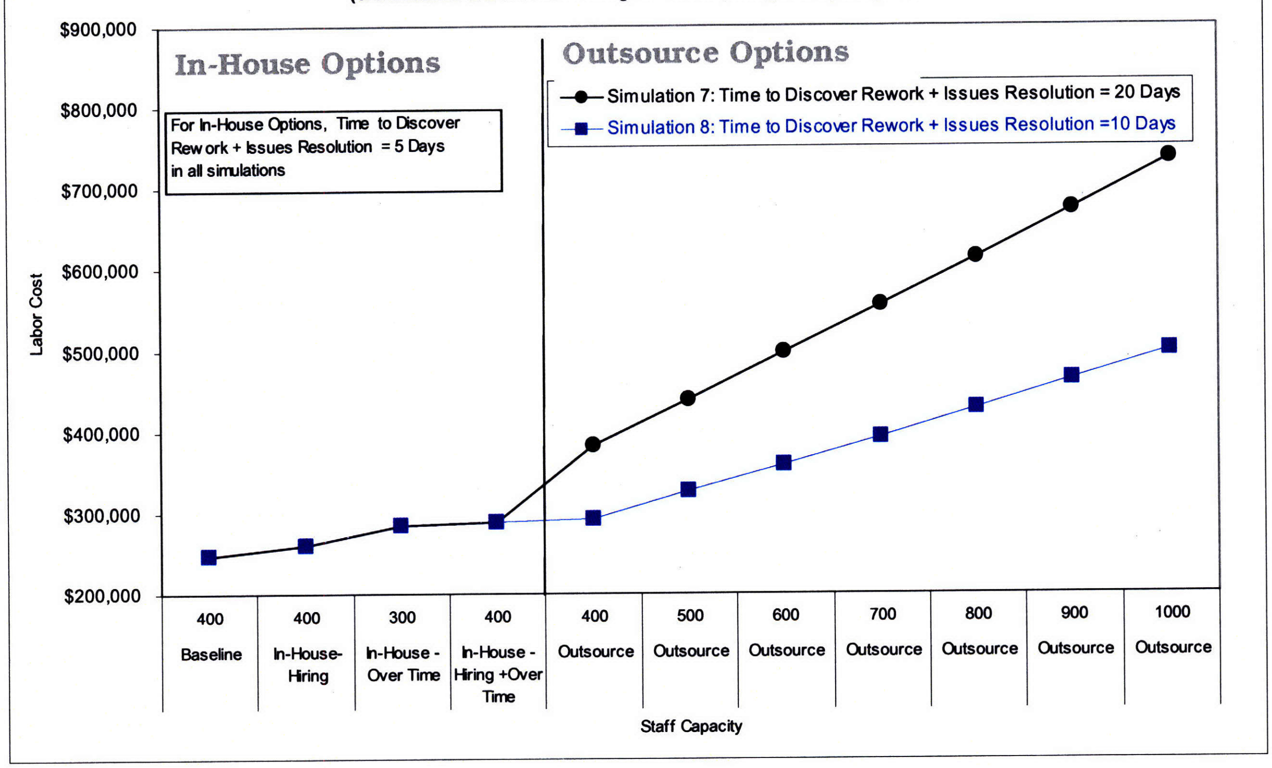


Figure 5.5b: Variation of Labor Cost for In-Hourse & Outsource Options
(Simulations7 & 8: Initial # of Designs = 474 x 2; Design Complexity = 2)

For Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days Table 5.5b, we see that the In-House Hiring option returns the best result in terms of *Engineering-Design-Lead-Time* and *Labor-Cost* which are 662 Days (7% over the Baseline target), and $260,633 (5% over the Baseline target) respectively. Outsourcing option are seen not to be viable in this case.

When Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* is reduced from 20 to 10 Days Table 5.5c, the Outsourcing options are still quite costly. For example, we see that a supplier with a staff of 500 can achieve an *Engineering-Design-Lead-Time* and *Labor-Cost* of 651 Days (5% over the Baseline target), but at a cost of $325,208 (31% over the Baseline target) respectively. Again, we see that as *Design-Complexity* increases, the more costly it becomes to outsource a design work.

5.7. Sourcing of Engineering Design Case 5: Impact of High Supplier Quality (60%), Mean-Time-to-Discover-Rework + Issues-Resolution on Engineering Design Lead Time and Labor Cost

Table 5.6a: Simulations 9 & 10

Simulations	Volume (# of Designs)	Design Complexity	Outsource Mean Time to Discover Rework + Issue Resolution (Days)	In-source Mean Time to Discover Rework + Issue Resolution (Days)	Quality
Simulation-9	474 x 1	1	20	5	60%
Simulation-10	474 x 1	1	10	5	60%

For this analysis, the *Initial Number of Designs* is 474 x 1, and *Design-Complexity* =1, and the Supplier Quality 60% (High) to study the dynamics on *Engineering-Design-Lead-Time* and *Labor-Cost.* As in the analysis in preceding section, only 50% of the require staff capacity is available In-House, or 200 staff. The additional required staff is then be made up by In-House options – Hiring, Over Time, and a combination of Hiring and Over Time that the OEM can explore as shown in Table 5.6a-c.

The OEM has the option to choose from suppliers with staff capacities between 400 to 1,000. In the simulations results shown in Table 5.6b, the In-House and Outsource options are assumed to have a *Mean-Time-to-Discover-Rework* + *Issues-Resolution* of 5 Days and 20 Days respectively. In Table 5.6c, the In-House *Mean-Time-to-Discover-Rework* + *Issues-Resolution* remains unchanged at 5 Days, while the *Mean-Time-to-Discover-Rework* + *Issues-Resolution* for the Outsource options is decreased from 20 to 10 Days.

<u>Supplier Quality = 60%</u>

One of the main motivations for Outsourcing is when the OEM wants to access expertise in a technology for example. The expertise of the supplier in the particular process or technology would translate into higher quality work. Let us assume that instead of the 52% Baseline Quality, the supplier expertise and processes enable it to attain a quality of 60% instead.

Table 5.6b shows a recalculation of Case 1. The In-House options – Hiring, Over Time, and a combination of Hiring and Over Time are maintained at the Baseline Quality of 52%, while the Outsourcing options have been recomputed with a supplier Quality of 60% as shown.

The chart of Figure 5.6a shows the results for the *Engineering-Design-Lead-Time* for:

- Simulation 9 : *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days and
- Simulation 10 : *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days

The chart of Figure 5.6b shows the results for the *Labor-Cost -Time* for:

- Simulation 9: *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days and
- Simulation 10: *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 10 Days

Table 5.6b: Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 20 Days

Simulation 9	**Staff Capacity**	**Volume (# of Designs)**	**Design Complexity**	**Mean Time to Discover Rework + Issue Resolution (Days)**	**Quality**	**g Design Lead Time (Days) - Discover Rework + Issues Resolution**	**Normalized to Baseline -- Discover Rework + Issues Resolutio**	**Labor Cost; Discover Rework + Issues Resolution = 20 Days**	**Labor Cost Normalized to Baseline**
Baseline	**400**	**474 x 1**	**1**	**5**	**52%**	**360**	**100%**	**$ 144,158**	**100%**
In-House- Hiring	400	474 x 1	1	5	52%	404	112%	$ 157,433	109%
In-House - Over Time	300	474 x 1	1	5	52%	476	132%	$ 142,525	99%
In-House -Hiring +Over Time	400	474 x 1	1	5	52%	409	114%	$ 161,567	112%
Outsource	400	474 x 1	1	20	60%	456	127%	$ 182,635	127%
Outsource	500	474 x 1	1	20	60%	428	119%	$ 213,708	148%
Outsource	600	474 x 1	1	20	60%	410	114%	$ 245,750	170%
Outsource	700	474 x 1	1	20	60%	399	111%	$ 278,892	193%
Outsource	800	474 x 1	1	20	60%	392	109%	$ 312,867	217%
Outsource	900	474 x 1	1	20	60%	387	108%	$ 347,775	241%
Outsource	1000	474 x 1	1	20	60%	384	107%	$ 383,083	266%

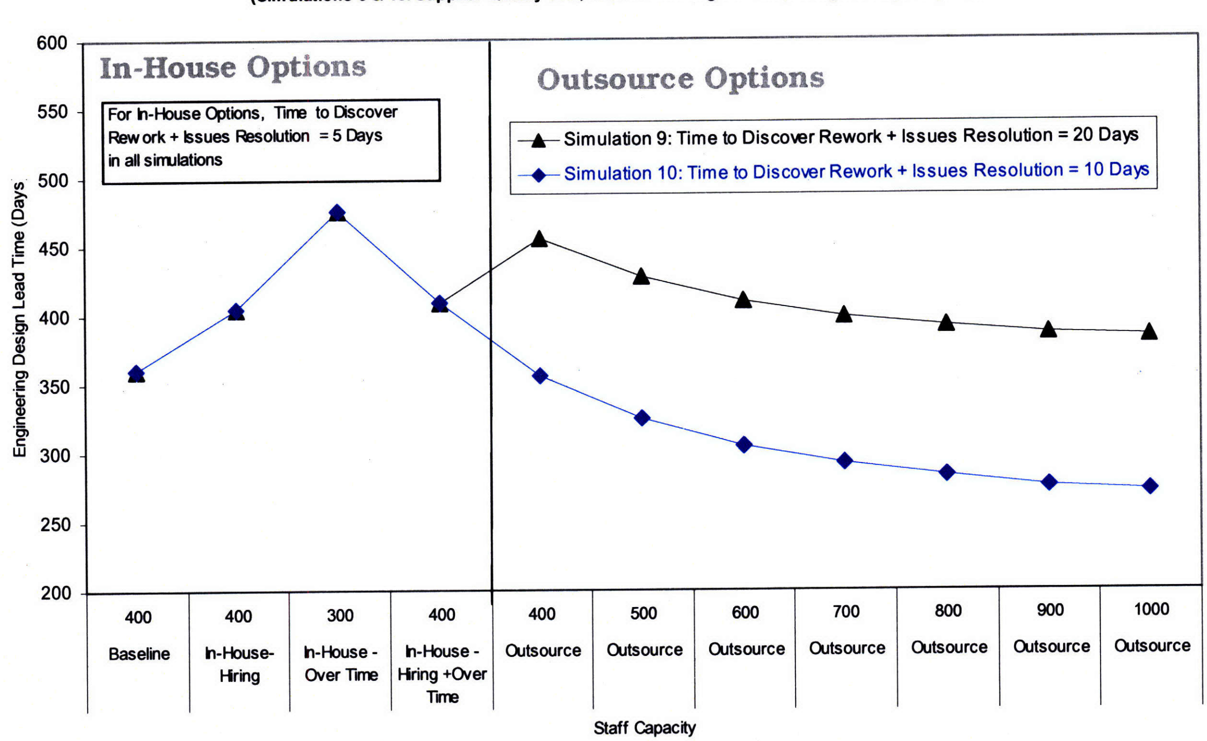
Table 5.6c: Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 10 Days

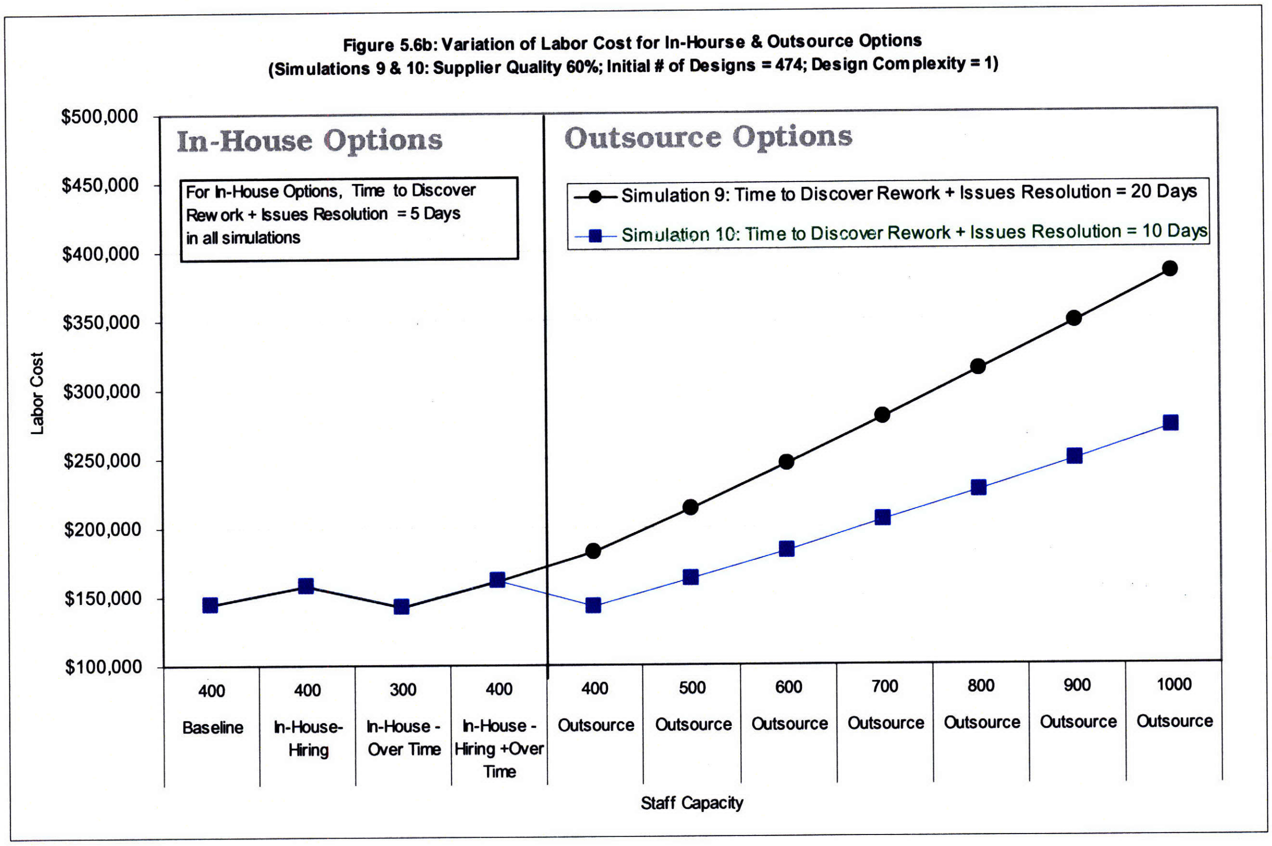
Simulation 10	**Staff Capacity**	**Volume (# of Designs)**	**Design Complexity**	**Mean Time to Discover Rework + Issue Resolution (Days)**	**Quality**	**Engineering Design Lead Time (Days); Discover Rework + Issues Resolution = 10 Days**	**Lead Time Normalized to Baseline**	**Labor Cost; Discover Rework + Issues Resolution = 10 Days**	**Labor Cost Normalized to Baseline**
Baseline	**400**	**474 x 1**	**1**	**5**	**52%**	**360**	**100%**	**$ 144,158**	**100%**
In-House- Hiring	400	474 x 1	1	5	52%	404	112%	$ 157,433	109%
In-House - Over Time	300	474 x 1	1	5	52%	476	132%	$ 142,525	99%
In-House -Hiring +Over Time	400	474 x 1	1	5	52%	409	114%	$ 161,567	112%
Outsource	400	474 x 1	1	10	60%	356	99%	$ 142,167	99%
Outsource	500	474 x 1	1	10	60%	325	90%	$ 162,042	112%
Outsource	600	474 x 1	1	10	60%	304	84%	$ 182,650	127%
Outsource	700	474 x 1	1	10	60%	292	81%	$ 203,992	142%
Outsource	800	474 x 1	1	10	60%	283	79%	$ 225,667	157%
Outsource	900	474 x 1	1	10	60%	276	77%	$ 248,025	172%
Outsource	1000	474 x 1	1	10	60%	272	76%	$ 271,083	188%

For Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* = 20 Days Table 5.6b, we see that the In-House Hiring option returns the best result in terms of *Engineering-Design-Lead-Time* and *Labor-Cost* which are 404 Days (12% over the Baseline target), and $157,433 (9% over the Baseline target) respectively. Outsourcing options are seen not to be viable in this case.

When Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* is reduced from 20 to 10 Days Table 5.6c, we immediately see the impact of the high Quality of the supplier. For example, we see that a supplier with a staff of 400 can achieve an *Engineering-Design-Lead-Time* and *Labor-Cost* of 356 Days (1% better than the Baseline target), and at a cost of $142,167 (1% better than the Baseline target) respectively. Thus even given similar Labor Rates, the supplier meets and marginally exceeds the targets for *Engineering-Design-Lead-Time* and *Labor-Cost* because of the supplier high Quality.

Figure 5.6a: Variation of Engineering Design Lead Time for In-Hourse & Outsource Options (Simulations 9 & 10: Supplier Quality 60%; Initial # of Designs = 474; Design Complexity = 1)





5.8. Sourcing of Engineering Design Case 6: Impact of Low Supplier Quality (40%), Mean-Time-to-Discover-Rework + Issues-Resolution on Engineering Design Lead Time and Labor Cost

Table 5.7a: Simulations 11 & 12

Simulations	Volume (# of Designs)	Design Complexity	Outsource Mean Time to Discover Rework + Issue Resolution (Days)	In-source Mean Time to Discover Rework + Issue Resolution (Days)	Quality
Simulation-11	474 x 1	1	20	5	40%
Simulation-12	474 x 1	1	10	5	40%

For this analysis, the *Initial Number of Designs* is 474 x 1, and *Design-Complexity* =1, and the Supplier Quality 40% (Low) to study the dynamics on *Engineering-Design-Lead-Time* and *Labor-Cost.* As in the analysis in preceding section, only 50% of the require staff capacity is available In-House, or 200 staff. The additional required staff is then be made up by In-House options – Hiring, Over Time, and a combination of Hiring and Over Time that the OEM can explore as shown in Table 5.7a-c.

The OEM has the option to choose from suppliers with staff capacities between 400 to 1,000. In the simulations results shown in Table 5.7b, the In-House and Outsource options are assumed to have a *Mean-Time-to-Discover-Rework* + *Issues-Resolution* of 5 Days and 20 Days respectively. In Table 5.7c, the In-House *Mean-Time-to-Discover-*

Rework + Issues-Resolution remains unchanged at 5 Days, while the *Mean-Time-to-Discover-Rework + Issues-Resolution* for the Outsource options is decreased from 20 to 10 Days.

<u>Supplier Quality = 40%</u>
Similarly, it is perfectly possible that the OEM is assuming that its supplier meets the Baseline Quality of 52%, but in reality the supplier is only working at a 40% Quality.

Table 5.7b shows a recalculation of Case 1. The In-House options – Hiring, Over Time, and a combination of Hiring and Over Time are maintained at the Baseline Quality of 52%, while the Outsourcing options have been recomputed with a supplier Quality of 40% as shown.

The chart of Figure 5.6a shows the results for the *Engineering-Design-Lead-Time* for:

- Simulation 9 : *Mean-Time-to-Discover-Rework + Issues-Resolution* = 20 Days and
- Simulation 10 : *Mean-Time-to-Discover-Rework + Issues-Resolution* = 10 Days

The chart of Figure 5.6b shows the results for the *Labor-Cost -Time* for:

- Simulation 9: *Mean-Time-to-Discover-Rework + Issues-Resolution* = 20 Days and
- Simulation 10: *Mean-Time-to-Discover-Rework + Issues-Resolution* = 10 Days

Table 5.7b: Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 20 Days

Simulation 11	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days); Discover Rework + Issues Resolution	Lead Time Normalized to Baseline	Labor Cost; Discover Rework + Issues Resolution = 20 Days	Labor Cost Normalized to Baseline
Baseline	400	474 x 1	1	5	52%	360		$ 144,158	
In-House- Hiring	400	474 x 1	1	5	52%	404	112%	$ 157,433	109%
In-House - Over Time	300	474 x 1	1	5	52%	476	132%	$ 142,525	99%
In-House -Hiring +Over Time	400	474 x 1	1	5	52%	409	114%	$ 161,567	112%
Outsource	400	474 x 1	1	20	40%	738	205%	$ 294,967	205%
Outsource	500	474 x 1	1	20	40%	693	193%	$ 346,042	240%
Outsource	600	474 x 1	1	20	40%	665	185%	$ 398,450	276%
Outsource	700	474 x 1	1	20	40%	645	179%	$ 452,142	314%
Outsource	800	474 x 1	1	20	40%	634	176%	$ 506,867	352%
Outsource	900	474 x 1	1	20	40%	626	174%	$ 562,575	390%
Outsource	1000	474 x 1	1	20	40%	620	172%	$ 619,082	429%

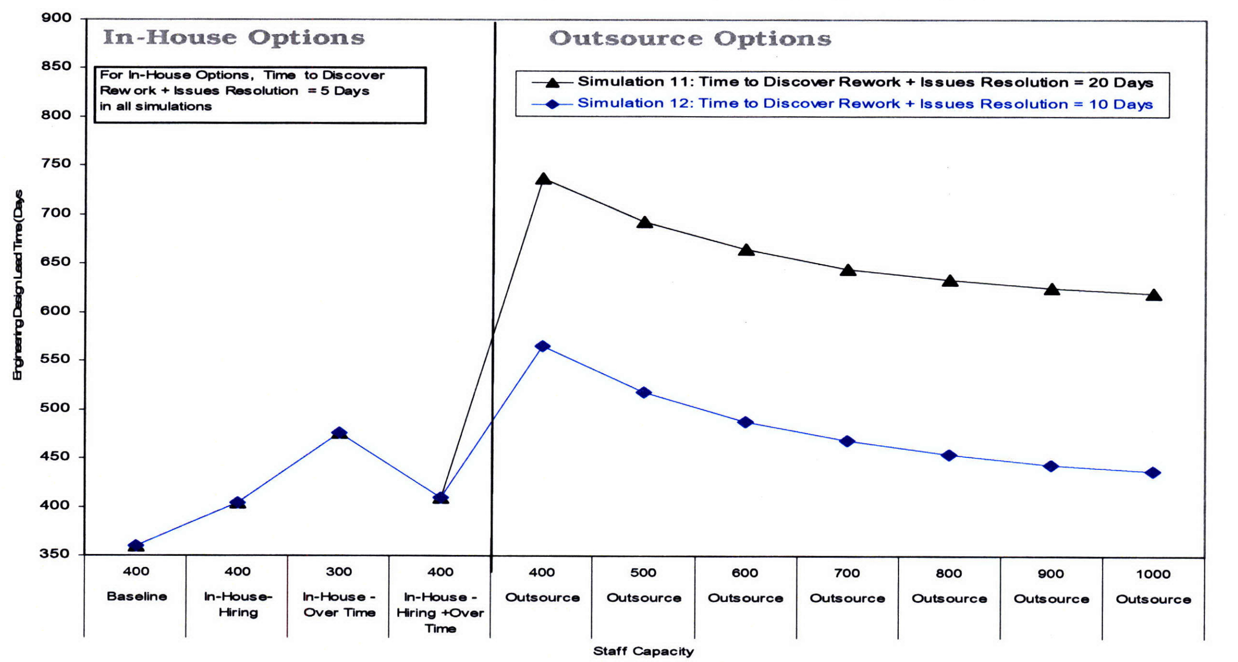
For Outsource Options *Mean-Time-to-Discover-Rework + Issues-Resolution* = 20 Days Table 5.7b, we see that the In-House Hiring option returns the best result in terms of *Engineering-Design-Lead-Time* and *Labor-Cost* which are 404 Days (12% over the Baseline target), and $157,433 (9% over the Baseline target) respectively. Notice the very poor *Engineering-Design-Lead-Time* and *Labor-Cost* of the Outsourcing options in this case. Therefore a supplier with poor Quality must be avoided at all cost..

When Outsource Options *Mean-Time-to-Discover-Rework* + *Issues-Resolution* is reduced from 20 to 10 Days Table 5.7c, we still see the Outsourcing options are still not viable because of the poor Quality of the supplier.

Table 5.7c: Outsourcing Mean-Time-to-Discover-Rework + Issues-Resolution = 10 Days

Simulation 12	Staff Capacity	Volume (# of Designs)	Design Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Engineering Design Lead Time (Days); Discover Rework + Issues Resolution = 10 Days	Lead Time Normalized to Baseline	Labor Cost; Discover Rework + Issues Resolution = 10 Days	Labor Cost Normalized to Baseline
Baseline	**400**	**474 x 1**	**1**	**5**	**52%**	**360**	**100%**	**$ 144,158**	**100%**
In-House- Hiring	400	474 x 1	1	5	52%	404	112%	$ 157,433	109%
In-House - Over Time	300	474 x 1	1	5	52%	476	132%	$ 142,525	99%
In-House -Hiring +Over Time	400	474 x 1	1	5	52%	409	114%	$ 161,567	112%
Outsource	400	474 x 1	1	10	52%	565	157%	$ 225,833	157%
Outsource	500	474 x 1	1	10	52%	518	144%	$ 258,542	179%
Outsource	600	474 x 1	1	10	52%	488	136%	$ 292,450	203%
Outsource	700	474 x 1	1	10	52%	468	130%	$ 327,308	227%
Outsource	800	474 x 1	1	10	52%	454	126%	$ 362,867	252%
Outsource	900	474 x 1	1	10	52%	444	123%	$ 399,225	277%
Outsource	1000	474 x 1	1	10	52%	437	121%	$ 436,417	303%

Figure 5.7a: Variation of Engineering Design Lead Time for In-Hourse & Outsource Options
(Simulations 11 & 12: Supplier Quality 40%; Initial # of Designs = 474; Design Complexity = 1)



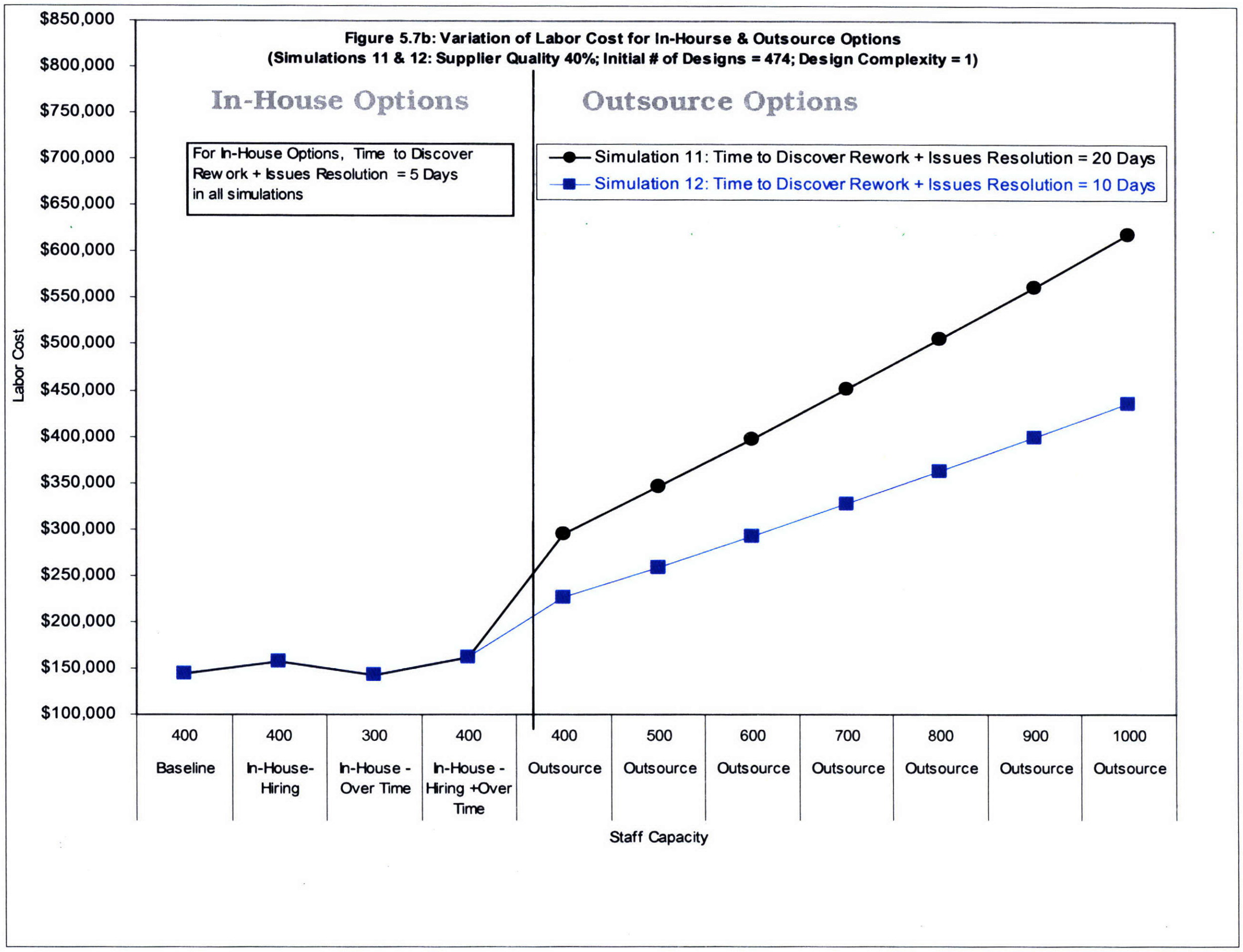


Figure 5.7b: Variation of Labor Cost for In-Hourse & Outsource Options
(Simulations 11 & 12: Supplier Quality 40%; Initial # of Designs = 474; Design Complexity = 1)
In-House Options
Outsource Options
For In-House Options, Time to Discover Rework + Issues Resolution = 5 Days in all simulations
Simulation 11: Time to Discover Rework + Issues Resolution = 20 Days
Simulation 12: Time to Discover Rework + Issues Resolution = 10 Days
Labor Cost
$850,000
$800,000
$750,000
$700,000
$650,000
$600,000
$550,000
$500,000
$450,000
$400,000
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
400 Baseline
400 In-House-Hiring
300 In-House - Over Time
400 In-House - Hiring +Over Time
400 Outsource
500 Outsource
600 Outsource
700 Outsource
800 Outsource
900 Outsource
1000 Outsource
Staff Capacity

6. Strategies for Sourcing Engineering Design Work – based on Example Cases Presented

In chapter five we simulated the sourcing of Engineering Design Work based on several variables that impact the generation of Engineering Change which result in rework and investigated their impacts on *Engineering-Design-Lead-Time* and *Labor-Cost.* In the current chapter, we employ the analysis of the last chapter to develop strategies for the sourcing of Engineering Design to enable a company make the right decision based on the dynamics of the specific case. The analysis will illustrate how dramatically different decisions could be reach because of the dynamics of the exogenous factors that impact Engineering Change generation – and consequently *Engineering-Design-Lead-Time* and *Labor-Cost.* The analysis is based on the Simulation Plan of Table 5.1 which is reproduced here for convenience.

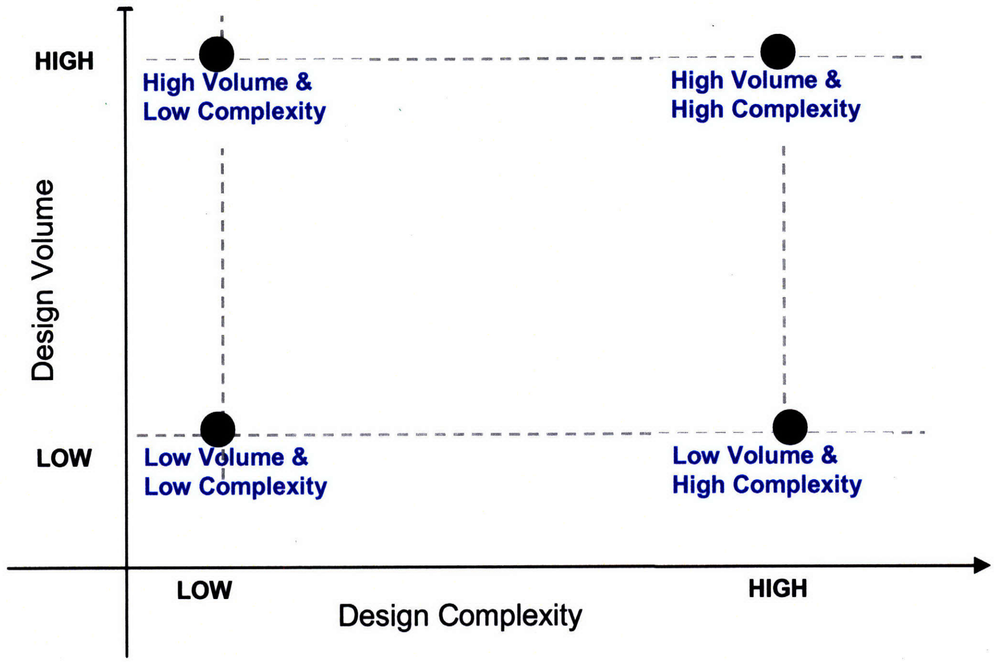
To gain an insight into Outsourcing to Low-Cost Regions, we reduced the Labor Rate used by 50% or $0.5 per Person-Day, and re-computed the cost of the Outsource options.

Table 5.1: Simulation Plan

Simulations	Volume (# of Designs)	Design Complexity	Outsource Mean Time to Discover Rework + Issue Resolution (Days)	In-source Mean Time to Discover Rework + Issue Resolution (Days)	Quality	Labor Cost: Normal/Low Cost Region
Simulation-1	474 x 1	1	20	5	52%	100% / 50%
Simulation-2	474 x 1	1	10	5	52%	100% / 50%
Simulation-3	474 x 2 = 948	1	20	5	52%	100% / 50%
Simulation-4	475 x 2 = 948	1	10	5	52%	100% / 50%
Simulation-5	474 x 1	2	20	5	52%	100% / 50%
Simulation-6	474 x 1	2	10	5	52%	100% / 50%
Simulation-7	475 x 2 = 948	2	20	5	52%	100% / 50%
Simulation-8	475 x 2 = 948	2	10	5	52%	100% / 50%
Simulation-9	474 x 1	1	20	5	60%	100% / 50%
Simulation-10	474 x 1	1	10	5	60%	100% / 50%
Simulation-11	474 x 1	1	20	5	40%	100% / 50%
Simulation-12	474 x 1	1	10	5	40%	100% / 50%

Figure 6.1 shows the reference model in which Volume (*Initial-Numb-of-Design-Work-to-Do*) and *Design Complexity* both have Low and High values resulting in the matrix shown.

Figure 6.1: Reference Model for the Sourcing of Engineering Design



6.1. Sourcing of Engineering Design Case 1: Mean Time to Discover Rework + Issue Resolution = 5 Days (for In-House Options); and 20 Days (for Outsource Options)

Figure 6.2a shows the Reference Simulations used in this analysis, while figure 6.2b shows the results. As can be seen in all cases, designing In-House offered the best option both in terms of *Engineering-Design-Lead-Time* and *Labor-Cost*. Design In-House was between 5% to 12% worse than the Baseline case. Note interestingly that for (*Initial-Numb-of-Design-Work-to-Do* = 474 x2; *Design-Complexity* =1*)*, Outsource Option with supplier staff capacity of 1,000 achieved a Lead Time of 91% - 9% better than the Baseline case – however, at a cost that was 227% of Baseline case – definitely, not a good Option as it appears, but will become attractive when outsourcing to a Low-cost region is considered.

Figure 6.2a: Reference Simulations

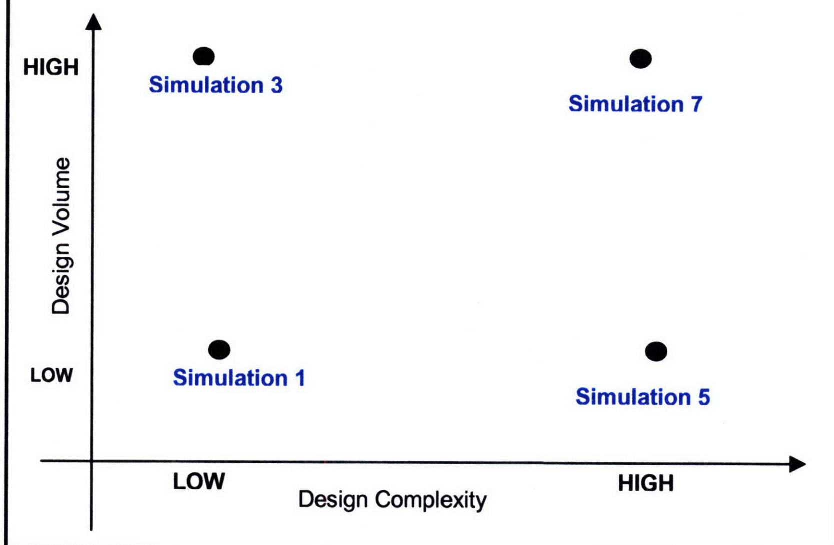
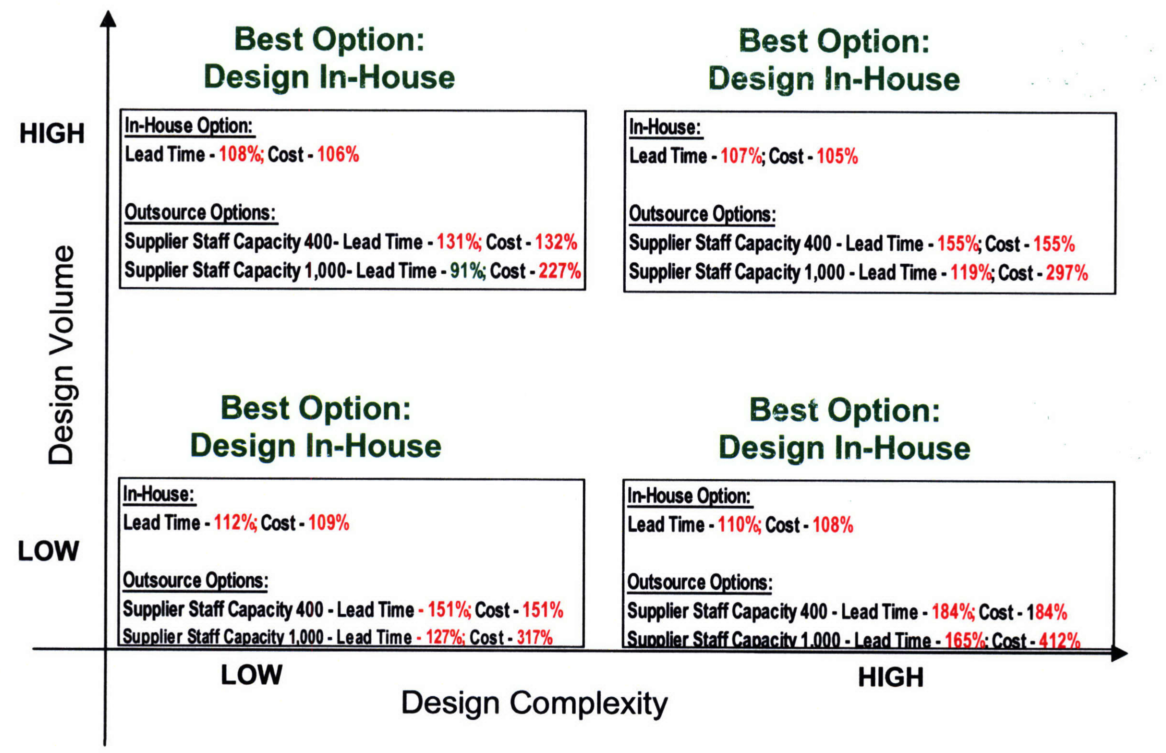


Figure 6.2b: Mean Time to Discover Rework + Issue Resolution - In-House - 5 Days
Mean Time to Discover Rework + Issue Resolution - Outsource - 20 Days



6.2. Sourcing of Engineering Design Case 2: Mean Time to Discover Rework + Issue Resolution = 5 Days (In-House Options); 10 Days (Outsource Options)

In this case the *Mean-Tim- to-Discover-Rework* + *Issue Resolution* = 5 Days (In-House Options); 10 Days (Outsource Options). Figure 6.3a shows the Reference Simulations used in this analysis, while figure 6.3b shows the results.

Again, as in the previous section, we see that in all cases, designing In-House offered the best option both in terms of Lead Time and cost. Design In-House was between 5% to 12% worse than the Baseline case. Note that for (*Initial-Numb-of-Design-Work-to-Do* = 474 x1; *Design-Complexity* =1*),* that is Low Volume, Low Complexity, Outsource Option with supplier staff capacity of 1,000 achieved a Lead Time of 89% - 11% better than the Baseline case, at a cost that was 223% of Baseline case.

Also for (*Initial-Numb-of-Design-Work-to-Do* = 474 x2; *Design-Complexity* =1*)*, that is High Volume, Low Complexity, Outsource Option with supplier staff capacity of 1,000 achieved a Lead Time of 68% - 32% better than the Baseline case, at a cost that was 171% of Baseline case – becomes an attractive option when Outsourcing to a Low-cost country is considered.

Figure 6.3a: Reference Simulations

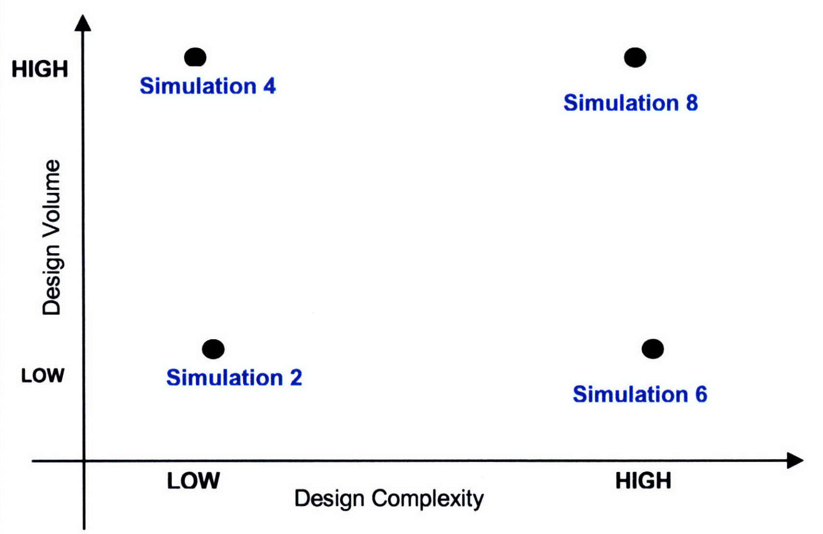
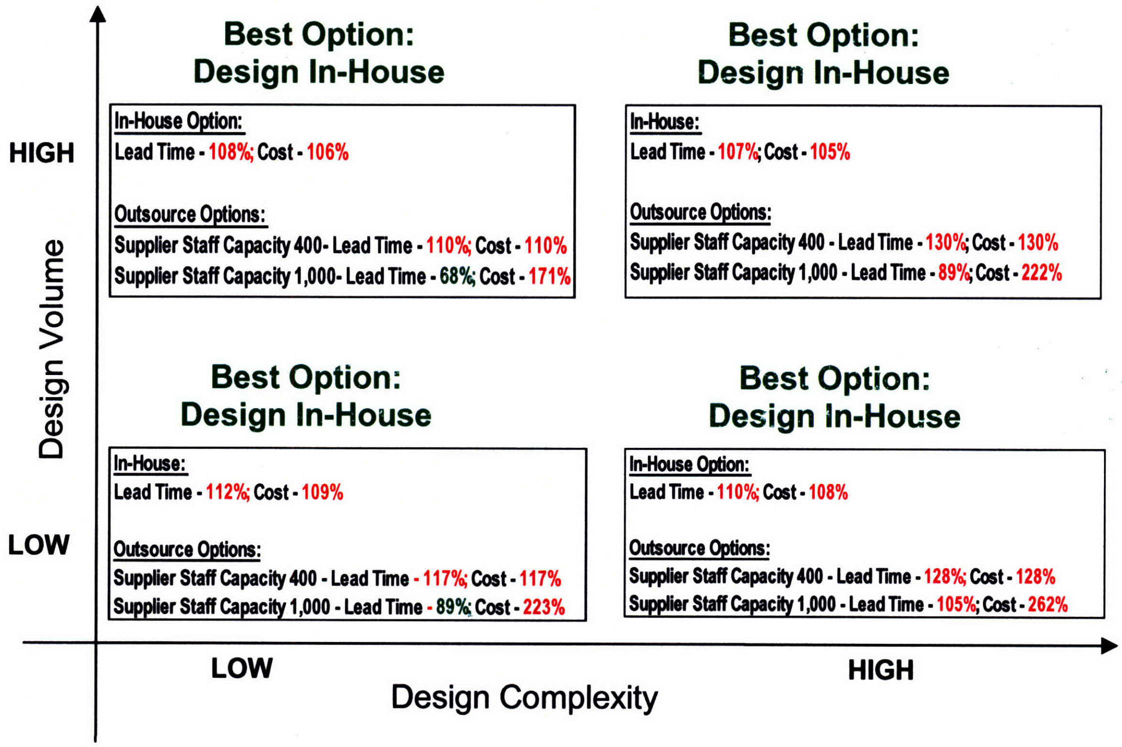


Figure 6.3b: Mean Time to Discover Rework + Issue Resolution - In-House - 5 Days
Mean Time to Discover Rework + Issue Resolution - Outsource - 10 Days



6.3. Sourcing of Engineering Design Case 3: Mean Time to Discover Rework + Issue Resolution = 5 Days (In-House Options); 20 Days (Outsource Options); Outsourcing is to a Low-cost Region

This is the same as section 6.1, but with the assumption that the Outsourcing is to a Low-cost region where the Labor cost is only 50% normal rate used in the analysis. Figure 6.4a shows the Reference Simulations used in this analysis, while figure 6.4b shows the results.

In this case, we see that for (*Initial-Numb-of-Design-Work-to-Do* = 474 x2; *Design-Complexity* =1*)*, that is High Volume, Low Complexity, Outsource Option with supplier staff capacity of 800 achieved a Lead Time of 97% and a cost also of 97% - 3% better than the Baseline case.

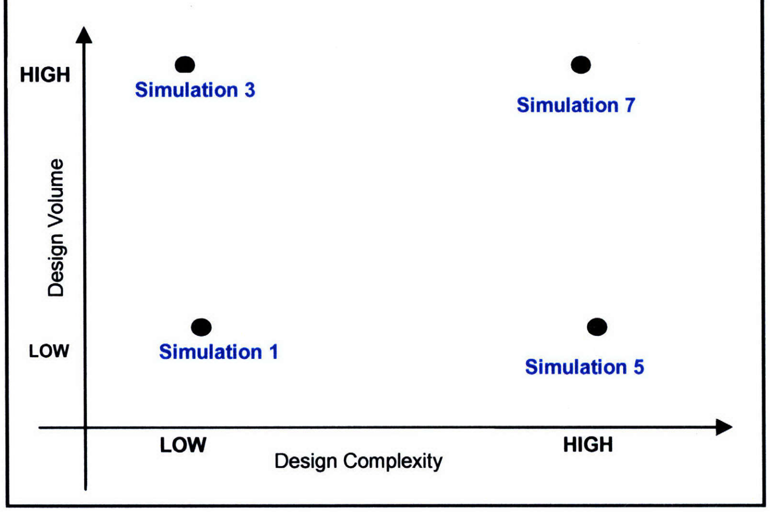


Figure 6.4a: Reference Simulations

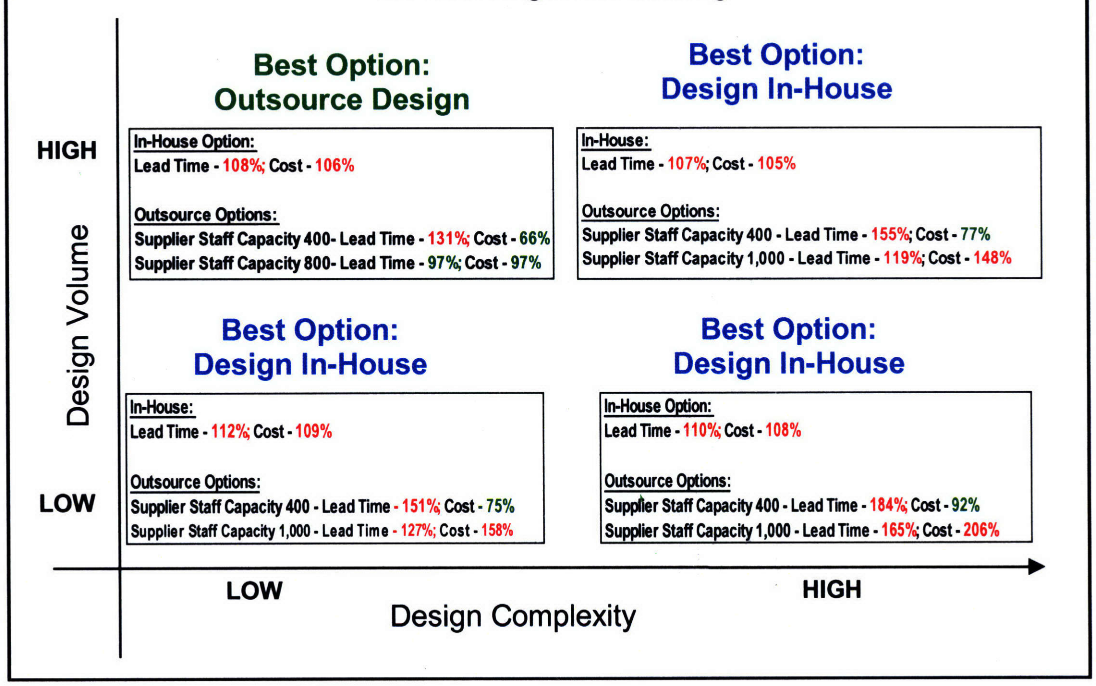


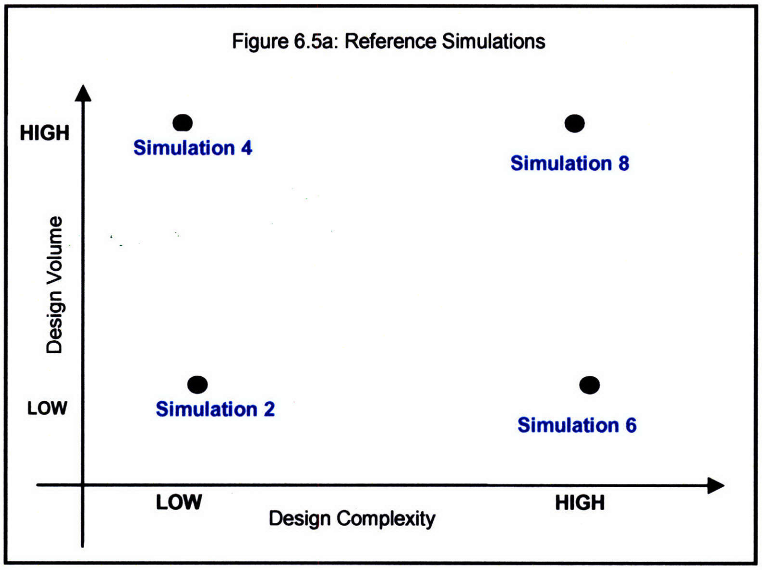
Figure 6.4b: Mean Time to Discover Rework + Issue Resolution - In-House - 5 Days
Mean Time to Discover Rework + Issue Resolution - Outsource - 20 Days
Low Cost Region Outsourcing

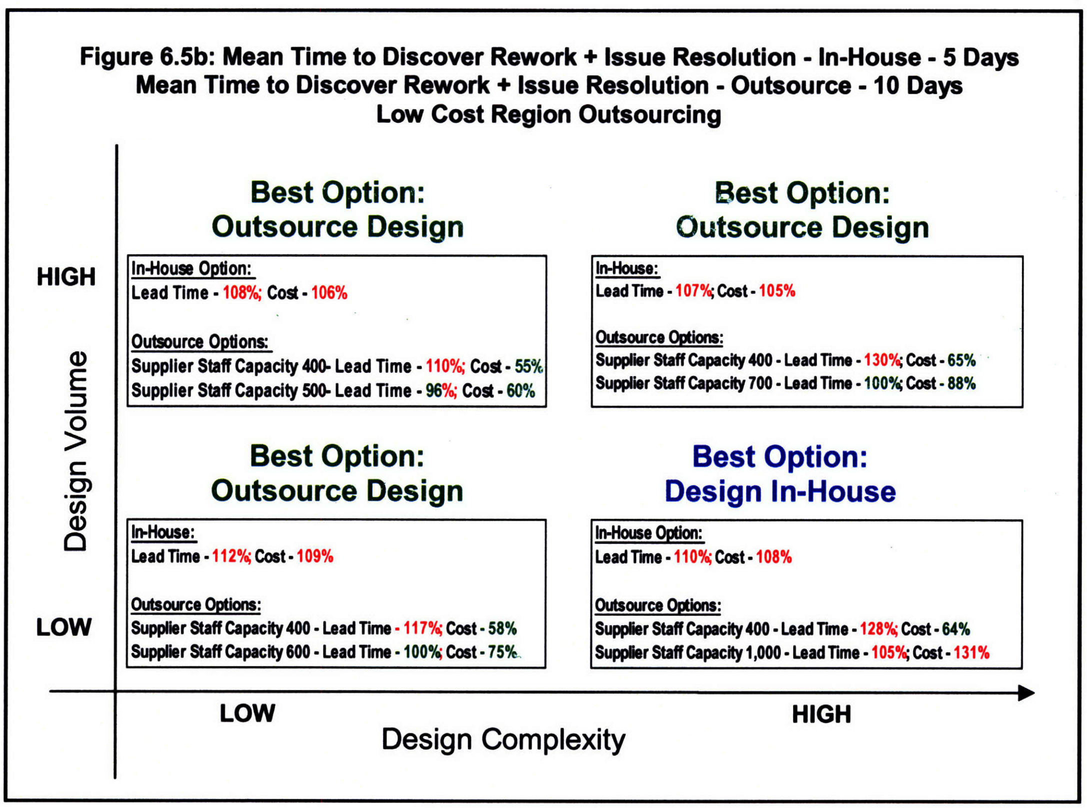
6.4. Sourcing of Engineering Design Case 4: Mean Time to Discover Rework + Issue Resolution = 5 Days (In-House Options); 10 Days (Outsource Options); Outsourcing is to a Low-cost Region

This is the same as section 6.2, but with the assumption that the Outsourcing is to a Low-cost region where the Labor cost is only 50% normal rate used in the analysis.

In this case the *Mean-Tim- to-Discover-Rework* + *Issue Resolution* = 5 Days (In-House Options); 10 Days (Outsource Options). Figure 6.5a shows the Reference Simulations used in this analysis, while figure 6.5b shows the results.

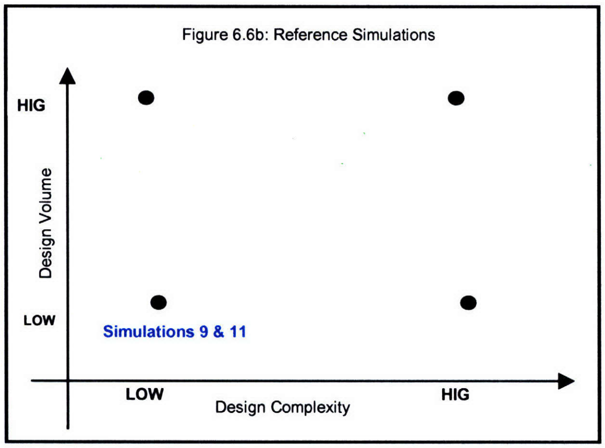
From Figure 6.5, we see that for all the Options except for (*Initial-Numb-of-Design-Work-to-Do* = 474 x1; *Design-Complexity* =2), that is Low Volume, High Complexity Outsource Options achieved Lead Time and cost better than the Baseline case.

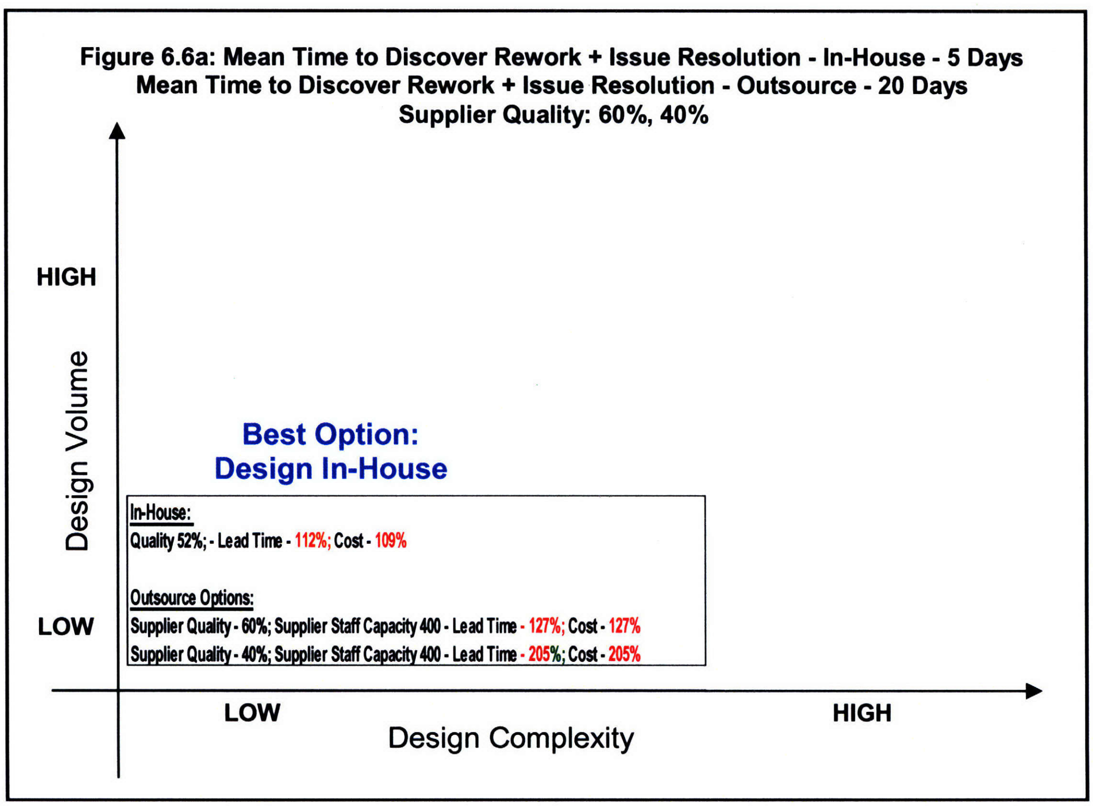




6.5. Sourcing of Engineering Design Case 5: Mean Time to Discover Rework + Issue Resolution = 5 Days (In-House Options); 20 Days (Outsource Options); Supplier Quality – 60% and 40%

Figure 6.6a shows the Reference Simulations used in this analysis, while figure 6.6b shows the results for the case *Initial-Numb-of-Design-Work-to-Do* = 474 x1; *Design-Complexity* =1, (Low Volume, Low Complexity) and two values for supplier Quality: 40% and 60%. As can be seen, the Design In-House Option gives the best Lead Time and cost of 112% and 109% of Baseline case respectively.





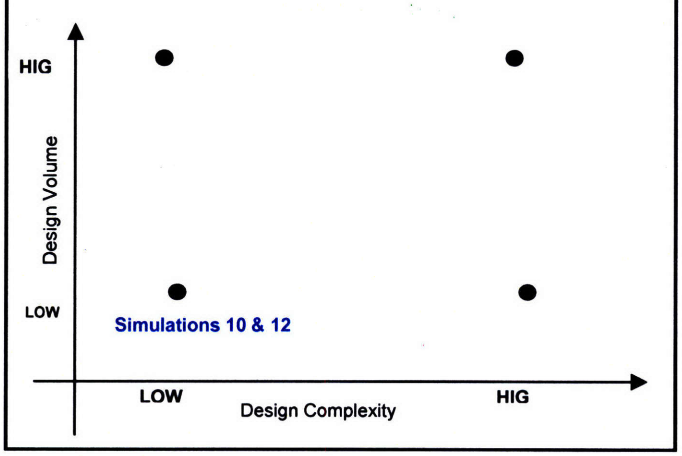
6.6. Sourcing of Engineering Design Case 6: Mean Time to Discover Rework + Issue Resolution = 5 Days (In-House Options); 10 Days (Outsource Options); Supplier Quality – 60% and 40%

In this section we reduce the *Mean-Time-to-Discover-Rework* + *Issue-Resolution* for Outsource Options from 20 to 10 days. Figure 6.7a shows the Reference Simulations used in this analysis, while figure 6.7b shows the results for the case.

Note the dramatic change: Outsource Option with supplier Quality of 60% gives Lead Time – 99% and cost – 99% which meets and marginally exceeds both the Baseline Lead Time and cost targets. Thus even without outsourcing to Lower-cost Region, we see that Outsourcing can indeed be a viable option when the supplier performance is higher than the performance of the OEM. As the graph of figure 5.7b shows, we see that even without Outsourcing to a Low-cost region, the OEM will meet both its cost and schedule targets with any suppliers with staff capacity of 400. This illustrates the importance of Supplier *Quality*.

Note that when supplier *Quality* decreases to 40%, the reverse is true: Outsourcing is not a viable option when the supplier performance is below that of the OEM. We see for example that when the supplier Quality is only 40%, Lead Time and cost are 157% of the Baseline. Thus, even if the OEM decides to outsource to a Lower-cost region where the Labor cost is only 50% the normal Labor rate, we see that while the supplier cost decreases to 78% of Baseline, its Lead Time is still 157%. The OEM would have to make the decision as to whether the Lead Time that is 57% higher than its Baseline is acceptable to it. Even when the supplier in the Lower-cost region is able to increase its staff capacity 2.5 times from 400 to 1,000 the Lead Time only decreases to 121% of Baseline - but the supplier Labor cost now jumps from 78% to 151%.

Figure 6.6b: Reference Simulations



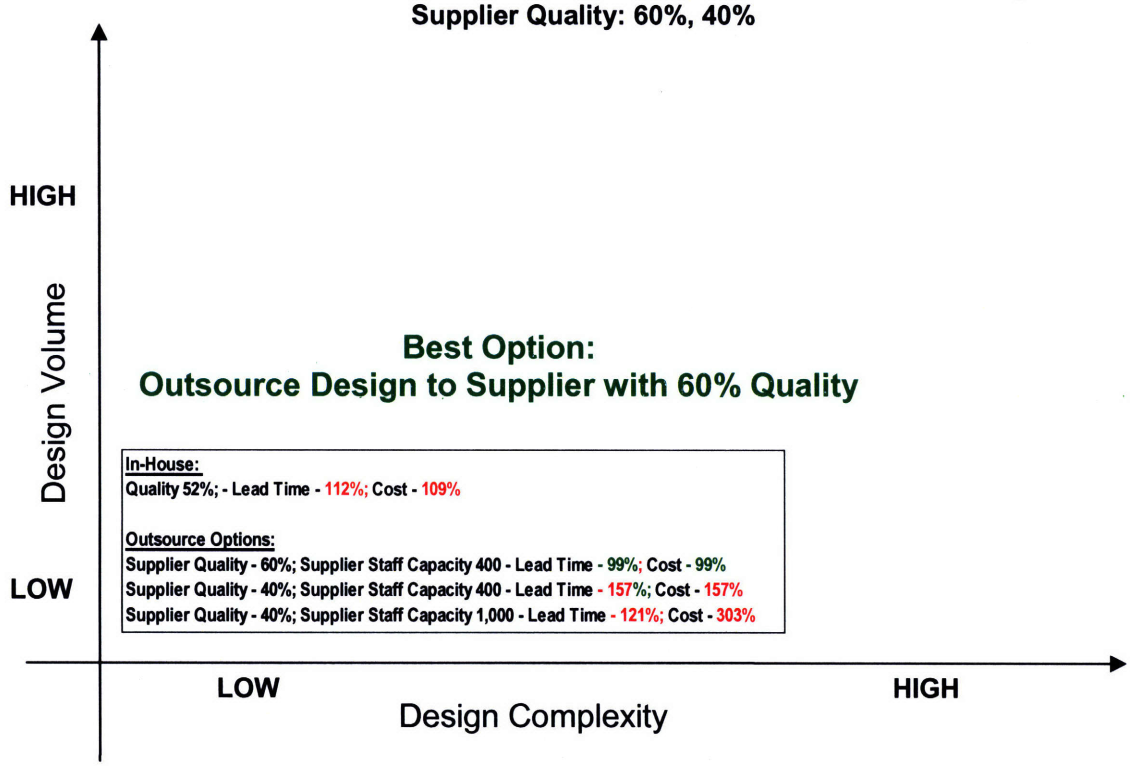


Figure 6.7a: Mean Time to Discover Rework + Issue Resolution - In-House - 5 Days
Mean Time to Discover Rework + Issue Resolution - Outsource - 10 Days
Supplier Quality: 60%, 40%

7. Conclusions

This thesis work has presented a System Dynamics model for the Strategic Analysis of Options in the Sourcing of Engineering Design. In order to investigate the impact of EC (Engineering Change) on Engineering Design Lead Times and Labor Cost, the model employed a number of factors which impact the generation of EC as exogenous variable to study the dynamics of EC on Engineering Design Lead Times and Labor Cost. These factors include: Quality, Design Complexity, Time to Discover Rework, Time for Issues Resolution, Hiring New and less experienced staff and Over Time work.

To enable the OEM make informed decision about sourcing a particular Design work, we employed the Systems Dynamics model developed to analyze and study the dynamics of the scenario in which an OEM faced with a staff capacity constraint because it has only 50% of the staff needed to finish the Design work explored its options as follows:

- Adopt an Over Time Strategy
- Adopt a Hiring Strategy
- Adopt a combination of Over Time and Hiring Strategy
- Adopt an Outsourcing Strategy

We simulated the model to investigate the dynamics of these variables in Outsourcing:

- *Mean-Time-to-Discover-Rework*
- *Time-for-Issues-Resolution*
- *Supplier-Quality*,
- *Design-Complexity*
- *Supplier Staff Capacity*
- *Staff Capacity*
- *Initial Number of Designs (Design Volume)*

We developed strategies for the sourcing of Engineering Design Work to enable a company make the right decision based on the dynamics of this specific case. The analysis illustrated how dramatically different conclusion could be reach because of the dynamics of the factors that impact Engineering Change generation – and consequently *Engineering-Design-Lead-Time* and *Labor-Cost.*

The analysis was based on a Baseline case where the Quality was 52%, and the Time to Discover Rework and Issues Resolution was 5 Days. To gain an insight into Outsourcing to Low-Cost Regions, we reduced the Labor Rate used by 50% or $0.5 per Person-Day, and re-computed the cost of the Outsource options, based on the set of example cases presented.

7.1. Principal Results - what management should know about the Dynamics of EC (Engineering Change)

7.1.1. The importance of Quality can never be Over-emphasized

Quality and Productivity are metrics widely used in industry to measure performance. The sensitivity analysis in this thesis shows that Quality is more critical than Productivity in Engineering Design, precisely because Quality impacts the generation of rework – resulting in Engineering Change, whereas Productivity does not. To compare the importance of Quality versus Productivity, we increased/decreased both Quality and Productivity by 10% from their Baseline values as shown in Table 7.1, and observed the dynamics (impacts) on Lead Time and Labor cost.

Table 7.1: Comparison of the Impacts of Quality & Productivity on Lead Time & Labor cost

	Quality (%)	Productivity (Designs per Person-Day)	Lead Time (Days)	Lead Time (%)	Change in Lead Time (%)
Baseline values	52%	0.01	360	100%	
10% Increase in Quality	62%	Baseline value	312	83%	-17%
10% Increase in Productivity	Baseline value	0.01	344	96%	-4%
10% Decrease in Quality	42%	Baseline value	477	127%	27%
10% Decrease in Prod	Baseline value	0.009	382	106%	6%

A 10% improvement in Quality is seen to reduce the Lead Time by 17%, while a similar 10% increase in Productivity results only in a 4% reduction in Lead Time. On the down side, a 10% deterioration in Quality results in a 27% increase in Lead Time, while a similar 10% decrease in productivity results only in a 6% increase in Lead Time. Thus we see that for similar changes, Quality produces an impact on Lead Time that is quadruple the impact produced by productivity. The reason for this can be found in the all-important "Effect of Prior Quality on Quality".

To understand the Effect of Prior Quality on Quality, note that rework generation is a function of Quality – the higher the Quality, the less the rework generated, and vice versa. Thus, at each iteration of the engineering design process, part of the work being done consists of reworking defects that were generated in the prior iteration or iterations. Therefore, the work to be accomplished at each stage or iteration is increased by the extent of the rework flowing into that stage from the previous stage or stages. "Effect of Prior Quality on Quality" makes Quality to have a compounding impact on Lead Time and Labor cost, and this impact increases as Quality deteriorates. This explains why a 10% improvement in Quality resulted in a 17% improvement in Lead Time as discussed above, whereas similar 10% deterioration in Quality resulted in a 27% deterioration in Lead Time. **The impact of low Quality can become dramatic as a result of the "Effect of Prior Quality on Quality".**

7.1.2. High Design Complexity coupled with Long Time to Discover Rework & Issues Resolution Result in Large Increase in Lead Time & Labor Cost

This analysis concludes that a high Design Complexity combined with Long Times to Discover Rework & for Issues Resolution greatly increase Lead Time & Labor cost. Table 7.2: shows that Impacts of High Design Complexity & Long Time to Discover Rework & Issues Resolution on Lead Time & Labor cost. We observe that when the Design Complexity = 1 (Low Design Complexity), increasing the Mean Time to Discover Rework & for Issues Resolution from 5 to 20 Days, increases Lead Time & Labor cost by 51%.

However, when the Design Complexity is 2 (High Design Complexity), increasing the Mean Time to Discover Rework & for Issues Resolution from 5 to 20 Days, now increases Lead Time & Labor cost by as much as 84%. The scenario painted here is illustrative of what an OEM could expect when Outsourcing Design work to a supplier. The Mean Time to Discover Rework & for Issues Resolution could see a dramatic increase (from 5 to 20 Days and even more); on account of less frequent communications between the OEM's and the supplier's design Engineers because of physical separation [31]; and also if a Design Change request hits a legal snag between OEM and supplier.

Table 7.2: Impacts of High Design Complexity & Long Time to Discover Rework & Issues Resolution on Lead Time & Labor cost

	Complexity	Mean Time to Discover Rework + Issue Resolution (Days)	Lead Time (Days)	Change in Lead Time (Days)	Change in Lead Time (%)	Labor Cost	Change in Labor Cost	Change in Labor Cost (%)
Baseline values	1	5	360			$ 144,158		
	1	20	545	185	51.4%	$ 217,608	$ 73,450	51.0%
Baseline values	2	5	419			$ 167,459		
	2	20	769	350	83.5%	$ 307,342	$ 139,883	83.5%

7.1.3. Even in a scenario where staff capacity is not a problem, Long Time to Discover Rework & Issues Resolution can become the critical factor that determines Design Lead Time

As the analysis in chapter 4 showed, if *Mean-Time-to-Discover-Rework & Time-for-Issues-Resolution* remains high at 20 days, then even when staff capacity was increased 2.5 times from 400 which is the baseline staff capacity to 1,000, it was still not possible to achieve the baseline schedule of 360. As shown in figure 4.75 and reproduced below for easy reference, the Lead Time achieved with a staff capacity of 1,000 was 457 – almost 100 days longer than the baseline Lead Time.

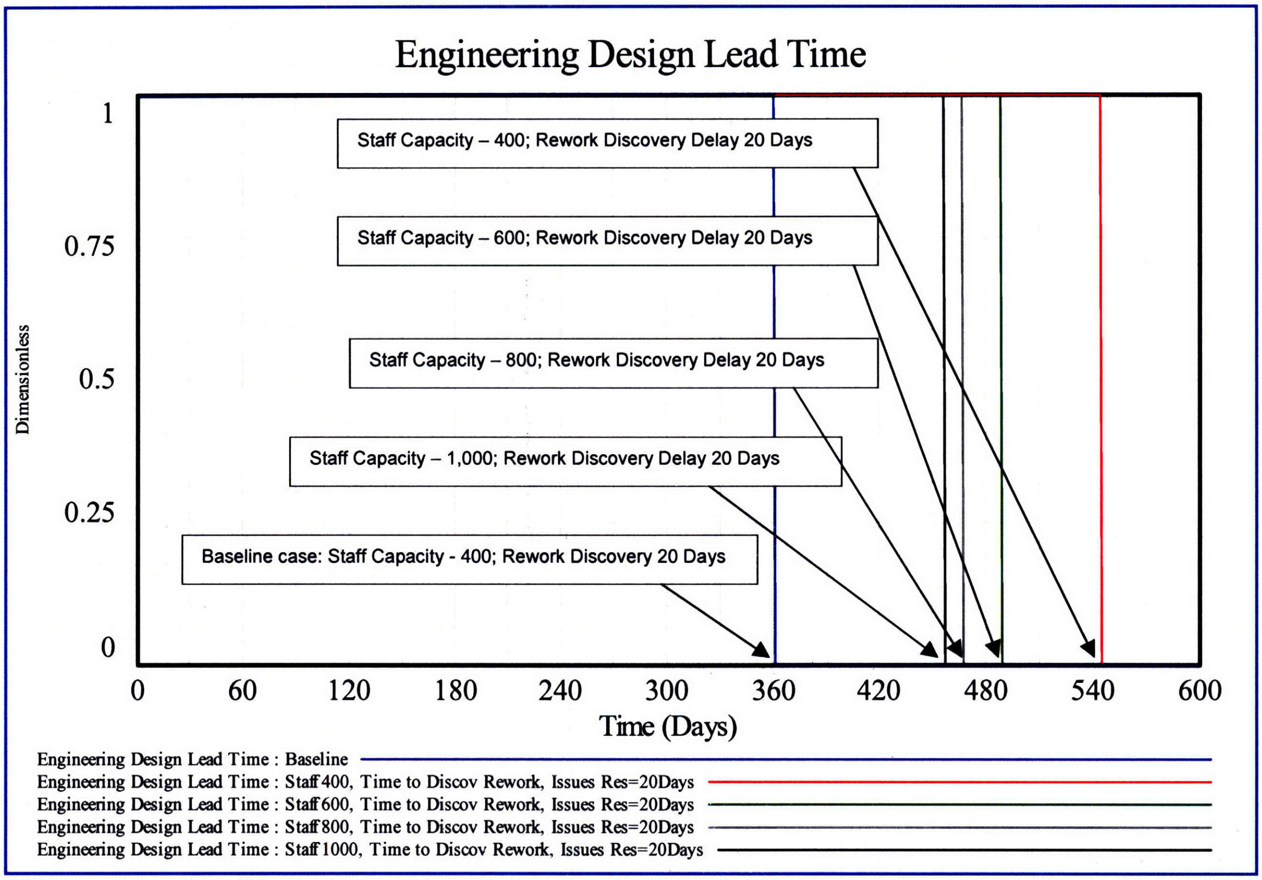


Figure 4.57: Staff Levels and Lead Time and Labor Cost

However, when *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* decreased to 10 days, then it was possible to meet and exceed the baseline schedule of 360. This is shown in figure 4.62 which is reproduced below for easy reference.

This is because the amount of design rework being generated is proportional to the staff capacity, and increases as the staff capacity increases. Therefore, the higher the staff capacity and longer the *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution*, the higher the volume of rework being generated. This means that the rework effort takes increasingly more time as staff level increases.

This will be particularly important when the reason why an OEM is outsourcing is to address staff capacity constraints. We see that if *Mean-Time-to-Discover-Rework* & *Time-for-Issues-Resolution* is not adequately controlled, then the OEM will be very surprised at the inability of the supplier to accomplish the work on schedule – even though the supplier has no staff capacity constraints.

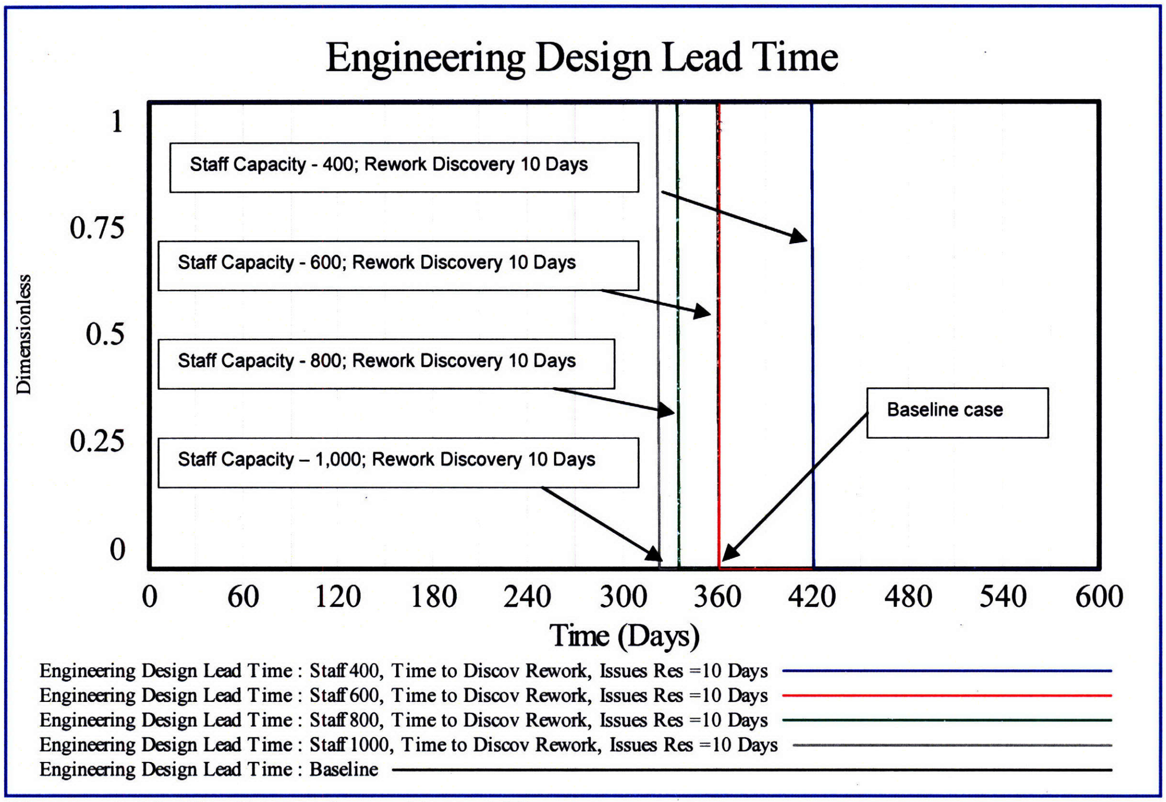


Figure 4.62: Staff Levels and Lead Time

7.1.4. Reducing the Time to Discover Rework is critical to successful Outsourcing

Rework are generated because (1) - Engineering Design is and iterative process, and (2) – the Engineering Design work is accomplished with less than perfect Quality. A critical factor that helps determine the Lead Time for the Design Engineering and Labor cost is the average Time it takes to Discover these reworks. This is important because the longer it takes to discover a rework, the higher the probability that downstream work is being accomplished base on defective upstream work – that is, the defect if not corrected propagates further and further into the Designs with time. Consequently, the longer it takes to discover the rework, the longer it takes to correct the defects because not only the original defect would have to be corrected. All work accomplished based on the original defect are automatically obsolesced and would have to be reworked as well.

The analysis concluded that if the Mean Time to Discover Rework and Issues Resolution is as high as 20 Days for the Outsource Option, compared to only 5 Days for the In-House Option, then the In-House sourcing Option of Hiring plus Over Time work is the best Option.

Under the above circumstances, outsourcing to a Low-cost Region only reduces the Labor cost, but has no impact on the longer Engineering Design Lead Time. For the outsourcing to be successful, the Mean Time to Discover Rework and Issues Resolution must be reduced by at least 50% to 10 Days for the Outsource Option, compared to 5 Days for the In-House Option.

As we also saw in the foregoing analysis, Time to Discover Rework and Issues Resolution, if not adequately controlled, can completely trump the availability of staff capacity as the critical factor that determines Lead Time and Labor cost. This is true when designing In-House as well as Outsourcing design work, but will be particularly critical in when Outsourcing because Time to Discover Rework and Issues Resolution are then typically longer.

7.1.5. Design Complexity

The complexity of the system under design is particularly sensitive to the Time to Discover Rework. Design Complexity is a measure of the degree of coupling between the subsystems of the system under design. Coupling determines the impact of a single Engineering Change on the whole system under design, because in a coupled system a change in the design of one subsystem automatically triggers Design Changes in the subsystems with which it interacts. The more coupled a system is the higher the degree of Design Changes a single EC will trigger. We therefore see how important the Time to Discover Rework is to Design Complexity. The analysis concluded that even when Mean Time to Discover Rework and Issues Resolution is 10 Days for the Outsource Option, compared to 5 Days for the In-House Option it was still not cost effective to Outsource complex designs.

7.2. Engineering Design Sourcing Strategies

7.2.1. Use only Suppliers who are highly specialized in specific technology areas

The key to successful outsourcing of design work will be finding Suppliers who are highly specialized in specific areas of technology and can therefore perform at a higher efficiency rate. In that case, the OEM simply adopts a Checklist approach to the outsourcing. However, if the Supplier is less knowledgeable than the OEM in the specific technology area, then a dilemma could arise. In order to get the job done, the OEM might then decide to work more collaboratively with the Supplier which typically includes actually sending SME (Subject Matter Experts) from the OEM to the Supplier site for extended periods of time to oversee and coach the Supplier staff. The danger in the Collaborative approach is that the OEM may unwittingly be transferring specific Technology know-how to the Supplier - Technology know-how that the Supplier would later give away to the competition, thereby putting the OEM at a disadvantage.

7.2.2. Maintain close communications with the Supplier during the Design phase

There are three basic types of technical communications among the Design Engineers. These include communications for: **Coordination, Information and Inspiration**. The benefits of clustering (co-location) OEM and supplier is that all three types of communication are enhanced. On the other hand, when the OEM and supplier are distributed (Non-co-located – as assumed here for the OEM and its Supplier), all three types of communications fall off sharply [31, 32].

The OEM must maintain close communications with the Supplier during the design phase as this is important in reducing the time it takes to discover rework. This is very important even when dealing with a Supplier that is highly skilled in the specific technology area. This close monitoring will enable the OEM to quickly find out when the design begins to deviates from specifications and to take corrective action.

7.2.3. Anticipate Issues Resolution to take longer time when Design is Outsourced, and Engineering Changes that could Trigger Contract Changes

When the design is done by a Supplier, then, then there is the possibility that the Supplier would interpret some EC request by the OEM as Contract Changes. Depending on the nature of the proposed ECs, the time for Issues Resolution could be much longer when the design is Outsourced compared to when the design is done In-House. Therefore, Issues Resolution could take longer in an Outsourcing scenario – matters could also get more complicated since two separate legal entities are involved.

7.2.4. Do not Outsource the Design of Complex Systems/Subsystems

We have noted the importance of the frequency of communications between the OEM and the Supplier design Engineers for successful Outsourcing. The study by the team lead by Prof Tomas J. Allen of MIT Sloan School of Management also found that modern media: E-mail, Telephone, Video conference, File sharing , etc are 'bandwidth limited', in more than the physical sense, and reached the conclusion that: "*It is very difficult to discuss a complex problem or an idea by e-mail or telephone*." This poses a major problem when design work is outsourced to a Supplier who is typically not co-located with the OEM.

This communications difficulty grows with the Complexity of the system being designed. A good example is the recent problems of the Boeing 787 Center Wing Box Spars [33, 34 and 35]. In the light of third delay in the 787 First Flight, announced on March 27, 2008 by Boeing it is being revealed that the cause of the delay is a design flaw in the 787's Center Wing Box Spars. Designed by Mitsubishi Heavy Industries of Japan, Boeing

Engineers found out recently that the center wing box, which connects the plane's wings to the fuselage and holds fuel, needed to be stiffened – meaning a Design Change is required. The problem originally was related to thickness shaved from structural spars made from composite as a weight-saving measure. Boeing has weight reduction as a key goal for the 787. Boeing is providing interim fixes which includes "aluminum stiffeners" alongside the spars for planes 1-6, which are currently being assembled in Boeing's Everett plant. Beginning with plane 7, a permanent fix, presumably thicker spars, will be incorporated. "*That required the addition of hundreds more clips and fasteners*", said Pat Shanahan, vice president and general manager of the 787 program [36].

Boeing is now doing the redesign of the 787 Wing Box in-House. It should not have been Outsourced in the first place.

7.3. Issues in Design Outsourcing

7.3.1. Design Outsourcing Traps - Design Outsourcing is Outsourcing Innovation

After spending years squeezing costs out of the manufacturing, management in many companies are now taking on their R&D operations as the next controllable cost [37]. Whereas the outsourcing of manufacturing sometimes makes clear financial sense, the ownership of design is often viewed as being core to a company's intrinsic value. Thus outsourcing of critical design functions to suppliers might raise a question as to how much intellectual property such a company really owns and how much of the profit from a successful product actually flows back to the company, rather than being paid out in licensing fees for technologies developed by its suppliers.

The next step in outsourcing appears to be the outsourcing of innovation itself. When companies in the advanced economies began selling factories and sending out manufacturing jobs to lower cost countries in the 1980s and 1990s in order to increase efficiency and focus on their core competencies, these companies insisted all the important R&D would remain in-House. Not any more. The growth of ODMs especially in the Electronics industry was fueled by OEM engaging their supplier initially only as **CM** (Contract Manufacturers), subsequently as **CDM** (Contract Design & Manufacturers), based on the OEM's original designs.

Some R&D Outsourcing questions include:

- There is the potential danger of fostering new competitors from the supplier companies themselves. Citing this specific case, Motorola award a CDM (Contract Design and Manufacturing) of millions of cell phones to BenQ Corp of Taiwan [37, 38]. In little time however, BenQ started selling phones last year in the prized China market under its own brand. That prompted Motorola to cancel the contract with BenQ. BenQ, through the CDM contract deal with Motorola gained enough knowledge of cell phone design. Based on this knowledge, all BenQ needed to do was give the proprietary Motorola product design a minor modification and come out with its own phone. Many EMS (Electronics Manufacturing Services) supplier companies have morphed into ODMs (Original Design Manufacturer) that way. They – the EMS supplier companies - first learn the art of product design by stealing ideas from the OEMs they manufacture products for; and subsequently begin marketing their own product designs. Motorola did cancel the BenQ contract, but has no way of taking back the know-how which BenQ acquired from it.

- Another risk is that brand-name companies will lose the incentive to keep investing in new technology. "It is a slippery slope," says Boston Consulting Group Senior Vice-President Jim Andrew. "If the innovation starts residing in the suppliers, you could incrementalize yourself to the point where there isn't much left.[37, 39]"

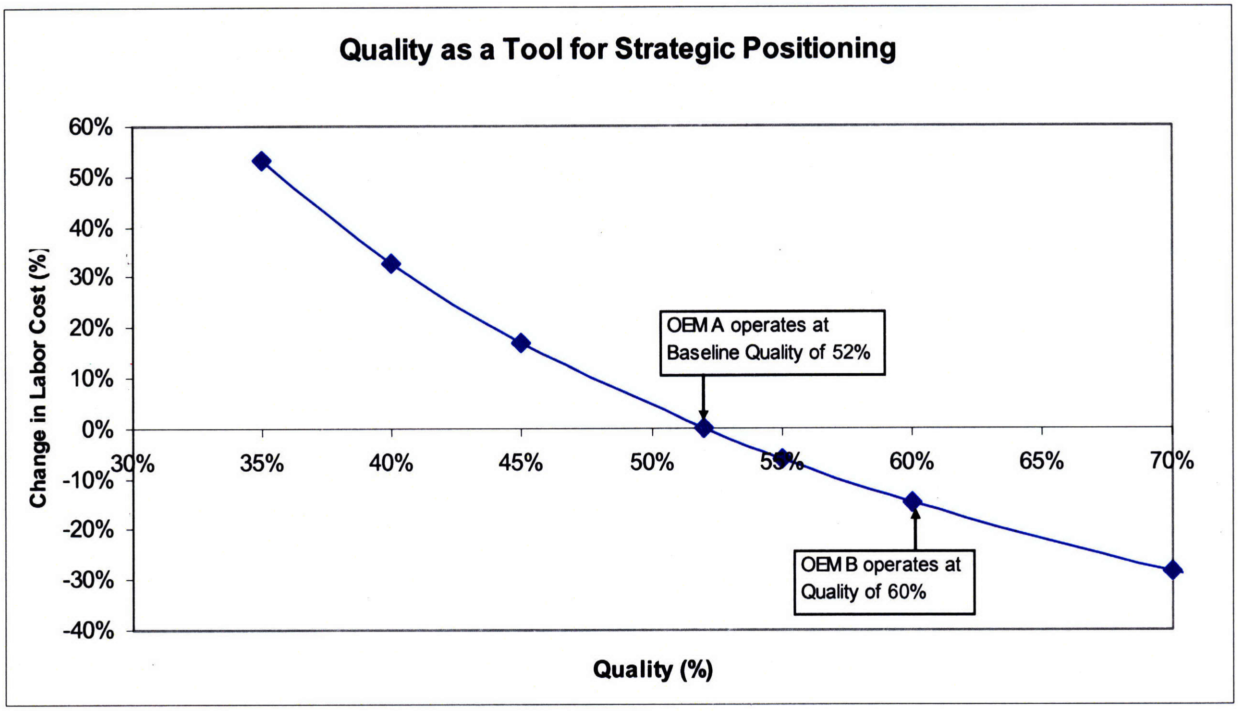
Many CDM suppliers have now morphed into **ODMs** (Original Design Manufacturers) [4] by initially learning the art of product design from the OEMs, and subsequently coming up with their own design which they can then market to any OEM for Branding [5, 6]. Under the ODM model, the Contract Manufacturer also owns the product design. So if the OEM now merely brands the product while the ODM (supplier) owns the design and intellectual property, the question might be rightly asked: where does the real power and clout lie; with the OEM of the supplier?

OEMs need to proceed carefully with innovation Outsourcing. **With the increasing Outsourcing of innovation, the OEMs run the risk of becoming increasingly irrelevant in the scheme of thing, and therefore more vulnerable**. They could easily be subverted by their suppliers if they are perceived as being mere "Clearing houses" with little significance in the value chain.

7.3.2. Importance of Quality in Business Strategy

The analysis in this thesis concludes that Quality is a very potent tool that a company can employ for its strategic positioning in the market place. The chart below shows the Change in Labor cost as a function of Quality. We consider two companies OEM A and OEM B operating in the same labor, product and market spaces. OEM A operates at Baseline Quality of 52% which is the breakeven selling price for a product developed by both companies.

The analysis shows that OEM B operating at a higher Quality of 60% achieves a 15% savings in Labor cost, simply on account of higher Quality. In the competitive environment this places OEM B at an advantage. First, OEM B has a bottom line (profit margin) that is 15% better than that of OEM A – on account of savings in Labor costs.



Second, OEM B may decide to lower its selling price below the current baseline price and still make a profit. If OEM B adopts this strategy, this may initially lead to a decrease in the company's top line revenues. But it will be only a matter of time before OEM B begins to take market share from OEM A, at which point OEM B sees improvements in its top and bottom lines – whereas OEM A experiences the opposite effect of shrinkage in revenues and profits.

This is precisely the strategy employed by Japanese companies such as Toyota to put tremendous pressure on competitors such as Ford and GM. The strategy often adopted by companies under pressure such as Ford and GM to remain competitive under such scenario is to Outsource to low cost regions such as India and China.

7.4. Supplier Development & Management

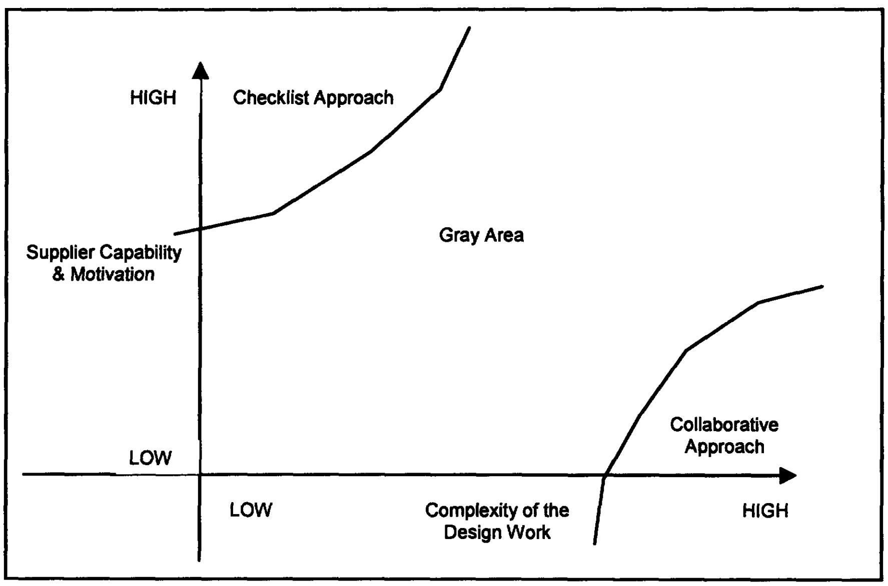
The OEM can adopt either a Checklist or a Collaborative approach.

A Checklist approach entails going to the supplier site once in a while to find a Checklist of problems to be solved, and has the benefits of being: Low cost, Standardized and Project management oriented. The disadvantage is that a Checklist approach only works well when the supplier has staff with the requisite skills and technology know-how, making close supervision unnecessary.

However, if the supplier staff lacks the requisite skills and technology know-how, then a Checklist approach cannot work, and the OEM must adopt a Collaborative approach which involves a close monitoring and supervision of the work done by the supplier staff.

The Collaborative approach entails sending subject matter experts to the supplier site for an extended period of time to coach the supplier staff. These Engineers must therefore have problem solving skills as well coaching ability. The major drawback of the collaborative approach is that the OEM may be unwittingly transferring technology know-how to its supplier and potentially creating future competition for itself. Also, the Collaborative approach is expensive and may mean the unavailability of personnel with critical skill if these are sent to train supplier staff.

Below is a general rule for applying a Checklist or a Collaborative approach to supplier management. For High Supplier Capability and Low Complexity of the Design work, the best strategy to adopt is Checklist. For Low Supplier Capability and High Complexity of the Design work, the best strategy to adopt is Collaborative. In between - Low Supplier Capability and Low Complexity of the Design work, and High Supplier Capability and High Complexity of the Design work are grey areas.



7.5. Boeing & Airbus Supply Chain Strategies - "Risk-sharing partnerships"

The logic of "Risk-sharing partnerships" have become a common strategy for "systems integrators" Boeing and Airbus.

Boeing and Airbus are now positioning themselves as Systems Integrators – outsourcing all manufacturing and increasing outsourcing design. Not only are Systems Integrators Boeing and Airbus outsourcing manufacturing and design work, they are also beginning to outsource development cost which hitherto they bore fully. Boeing started the new trend which is called "risk-sharing partnership" with its 787 Dreamliner in which suppliers are not simply building to Boeing specifications. Indeed, they are being given the freedom, and the responsibility, to design the components and to raise billions of dollars in development costs that are usually shouldered by Boeing [40].

In a new risk-sharing partnership, Boeing outsourced most of the design and construction of the 787, along with up to 40 percent of the estimated $8 billion in development costs to subcontractors in six other countries and hundreds of suppliers around the world. Mitsubishi of Japan, for example, is making the wings, a particularly complex task that Boeing always reserved for itself. Messier-Dowty of France is making the landing gear and Latecoere the doors. Alenia Aeronautica of Italy was given parts of the fuselage and tail [41].

In the past, Boeing has never farmed out so much work to so many partners — and in so many countries, up to 80% as it did with the 787. The outsourcing is so extensive that Boeing acknowledges it has no idea how many people around the world are working on the 787 project.

Based on the massive outsourcing and risk-sharing, Boeing had planned to bring the 787 to market in four and a half years, which is 16 to 18 months faster than most other models – if everything worked as planned. However, as Boeing would find out the hard way, this was only the plan. As is now well known, the plan has hot worked nearly as well in practice with the 787 Deamliner first flight delayed for the 4th time the April due to supplier related problems – see below.

Boeing is said to be the most parochial of aircraft makers with only about 2 per cent of the Boeing 707 built outside the US in the 1950s, but it is now part of a revolution promoting massive outsourcing of both design and manufacturing. In reality, in return for this risk-sharing capital, Boeing is giving away invaluable intellectual property .

The most ardent critic of the trend at Boeing is David Pritchard, a researcher at the State University of New York who laments the "strategic destruction" of the US aerospace industry, arguing that Boeing is giving away intellectual property in return for capital. Mr. Pritchard contends that Boeing is "helping suppliers in Japan and China to develop technology they will use to make their own aircraft" [42].

According to a news article in Flight International dated in the 12/12/06, Fifty per cent of the aerostructures work on the Airbus A350 XWB (eXtra Wide Body) [43] will be outsourced to risk-sharing partners, says Airbus chief executive Louis Gallois, which "we anticipate will be €1.8 billion ($2.4 billion) of the development costs".

We see from the above statement of Airbus that outsourcing of risk, or sharing of development cost is an industry trend – just as the outsourcing of manufacturing and increasingly the outsourcing of design. The Aerospace industry where Boeing is a player is dynamic and changing and Boeing must learn to adapt to its changing business environment if it is to survive. It must be clearly stated that risk-sharing is not necessarily the cause of loss of intellectual property. What causes the loss of intellectual property is the outsourcing of design work – to a supplier with less technology know-how.

The development cost of these new aircrafts are huge, and the failure of a single aircraft in the market place can cripple either Boeing or Airbus. Therefore, the "Risk-sharing partnerships" is a good business strategy for the systems integrators, enabling them to survive any major product failure.

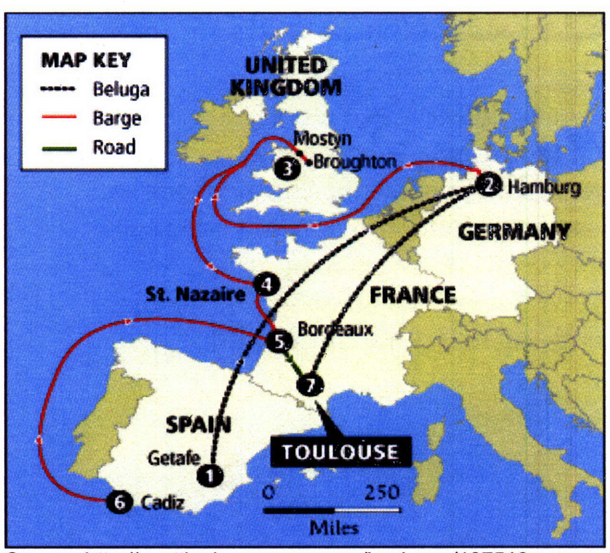
7.6. Boeing & Airbus Supply Chain Strategies - *3-Dimensional Concurrent Engineering* (i.e. integrating product, manufacturing & supply chain strategies)

This comparison is made between Boeing 787 and Airbus A380.

Airbus A380

Rather than assemble the A380 Superjumbo jet in one production facility, the Airbus build pieces of the aircraft at sites throughout Europe. Those pieces will then be brought to a new plant in Toulouse for Final assembly [22]. Logistically it will be a challenge because of the size of the parts. Some are so large that even the company's own Beluga plane will be too small to transport them [44].

1. Rear fuselage is built in Getafe, Spain and flown to Hamburg.
2. The aft fuselage, which is built near Hamburg along with the forward fuselage, is attached to the rear fuselage.
3. The assembled rear and aft fuselage and the forward fuselage are transported to Mostyn where they pick up the wings of the plane that were produced in Broughton.
4. The ship continues on to St. Nazaire where the nose section and center fuselage are built. The nose is attached to the forward fuselage at this point.
5. The ship then continues on to Bordeaux.
6. The belly fairing and horizontal tailplane are produced in Cadiz and shipped to Bordeaux.
7. All the parts are shipped from Bordeaux to Toulouse for final assembly.



Source: http://seattlepi.nwsource.com/business/127513_comparison20.html

Boeing 787

The 787 is remarkable for the degree to which Boeing has outsourced production around the world. Boeing itself is responsible for about 10 per cent by value tail fin and final assembly. The rest is done by 40 partners, with the wings built in Japan, the carbon composite fuselage in Italy and the US and the landing gear in France [45].

The Airbus A380 product integration and supply chain strategies are better because most major aircraft system manufacturing are clustered in Europe as summarized above. Boeing 787 product integration and supply chain strategies are too far flung worldwide that very long lead times will be a problem when the 787 goes in to full production.

For example, "in this Boeing statement dated in **EVERETT, Wash., April 25, 2007** "Manufactured by Alenia Aeronautica at its facility in Foggia, Italy, the horizontal stabilizer is transported in five pieces - the left and right stabilizer, two elevators and a center. The shipment configuration measures nine feet wide, 13 feet high and is 42 feet long. It was delivered to Boeing late yesterday via the Dreamlifter, a specially modified 747-400 used to transport 787 major assemblies. The horizontal stabilizer was loaded into position in the 787 final assembly bay earlier today. The completed assembly has a wing span of approximately 62 feet and measures 32 feet fore/aft." "In the coming weeks we will receive other major assemblies for the first Dreamliner," said Scott Strode, 787 vice president of Airplane Definition and Production [46, 47].

The Boeing 787 supply chain is too long making it more vulnerable than the A380 supply chain. The A380 supply chain could also be better. For example, it was more of a political decision to put the production of the wings of the aircraft in Broughton, Wales, given that it was a well known fact that those very large wings will pose significant transportation problems. The A380 wings are so large that they do not fit in the company's "Beluga" specially enlarged jets for transportation to Toulouse for final assemble. Instead, large A380 parts such as the wings are brought by ship to Bordeaux, and then transported to the Toulouse assembly plant by a specially enlarged road. It would have made more sense economically to produce the winks in or near the final assembly in Toulouse [48].

Both companies are embracing the global supply chain strategy. We already see Airbus with the concept of "Delocalisation" with outsourcing to China. The strategy for Airbus is simple – relocate production to China for two reasons: 1-exploit the cheap labour and 2- target the huge China aircraft market. Boeing is taking a harder look at the large-scale outsourcing of design in view of its recent setbacks. However, Boeing is unlikely to renounce the global supply chain strategy definitively. Boeing has no option but to adopt the global supply chain strategy if it is to remain competitive, versus Airbus [49].

7.7. Robustness of the Supply Chain – Lessons from the Boeing 7E7 Dreamliner experience & Airbus A380

Both the Airbus A380 and the Boeing 787 Dreamliner have encountered numerous problems related mainly to supplier issues [50, 51 and 52].

7.7.1. Causes of the problems

Airbus A380 Delays

On 3rd October 2006, Christian Streiff, then Airbus President and CEO announced the delay in the delivery of the Airbus 380 [53]. Mr. Streiff attributed the cause of the delay to what he called "a big flaw – one weak link in the chain: that of the design of the electrical harnesses installation in the forward and aft fuselage." This is the section 19 problem. He said that the root cause of the issue is that there were incompatibilities in the development of the concurrent engineering tools to be used for the design of the electrical harnesses installation. Quite simply, while the A380 is the most-advanced and modern plane ever made, the wiring harness installation design package in the forward and rear fuselage could not keep pace with the rest of the aircraft program. Also, the learning curve for wiring harness changes was too steep during the complex development phase. Airbus had to update and harmonize the 3D- design tools and data base.

Streiff insisted that the "root cause" of the delays remained in the complexity of installing the plane's hundreds of kilometers of electrical wiring, which drive everything from navigation systems to seat-back entertainment consoles. The parent company of Airbus, the EADS said that "The amount of work to be done to finalize the installation of the electrical harnesses into the forward and rear section of the fuselage had been underestimated in June," [54], referring to the explanation given when Airbus announced a six-month delay that shocked investors and customers and sent EADS shares tumbling 26 percent.

Boeing 787 Delays

Originally, before Boeing realized the scale of its supply-chain and production problems with the all-new 787, it had planned for the aircraft to make its first flight in the third quarter of 2007 and to deliver the first Dreamliner to a customer in May 2008. The First flight of the 787 will move into the Q4 of 2008 instead of the end of the Q2 of 2008. The first delivery of a 787 to a customer (All Nippon Airline of Japan) is now planned for the 3Q of 2009 instead of Q1 of 2009, the target Boeing had set in January when it delayed the 787 first-flight and test schedule [55, 56]. The two earlier delays were both attributed to assembly problems rather than issues with the aircraft's design. The third delay was due to design problem.

On September 5, 2007, Boeing announced a 3-month delay to the first flight
Causes of 1st Delay:

- (1)- First flight planned for August 27, 2007 was postponed on August 10, 2007. Inadequate supplies of highly engineered fasteners, prompting Boeing suppliers to use temporary fasteners on Dreamliner One – the First 787 Aircraft, (2)- need for more software code for the flight control system.

- Alcoa is the supplier of the highly specialized fasteners used in the composite carbon fiber fuselage of the 787. The cause of the shortage is said to be the booming demand for aircraft. Assembly of the Dreamliner and the new Airbus super-jumbo A380 increased demand for the specialized fastener products by some 20 percent. Alcoa had cut about 40 percent of its fastener workforce in a cutback when aircraft orders plunged following the September 11, 2001 terrorist attacks.

- Boeing had had approved the use temporary fasteners on early 787 airframes while a shortage of flight-worthy fasteners was being addressed. The source of the slowdown in progress on 787 originated by the use of these temporary fasteners on the Dreamliner One in a rush by Boeing to meet the planned July 8th, 2007 roll out. Boeing supply chain partners were said to have procured these over-the-counter fasteners which were painted red and installed in place of flight-worthy permanent fasteners. The news source (www.flightglobal.com) even claims that these fasteners were purchased from run-of-the-mill chain hardware stores, including Home Depot and Ace Hardware [57].

- Boeing was thus forced to comb through the Dreamliner One aircraft at its Everett, WA plant to locate, document and replace all of the temporary fasteners to prevent a single non-flight-worthy fastener from flying. This task was painstakingly slow for two reasons: firstly, it appears that Boeing suppliers had installed these fasteners without adequate documentation. Boeing assembly teams in Everett had to allocate significant resources for identifying and replacing the temporary fasteners. Secondly, is the challenge in physically replacing these fasteners in the carbon composite body of the 787: When it came time to install the flight-worthy fasteners, the removal of the temporary fasteners damaged some of the composite parts of the aircraft causing time-consuming repairs [58].

On October 10, 2007 a further 3-month delay to the first flight and a six month delay to first deliveries was announced
Cause of 2nd Delay:

- Boeing announced a 3-month delay of first flight, blaming the problems with its foreign and domestic supply chain and the continuing inadequate supplies of flight-worthy fasteners as well as incomplete software.

Cause of 3rd Delay announced March 27, 2008.

- The 787's Center Wing Box Spars design. Designed by Mitsubishi Heavy Industries of Japan, Boeing Engineers found out recently that the center wing box, which connects the plane's wings to the fuselage and holds fuel, needed to be stiffened – meaning a Design Change is required. The problem originally is related to thickness shaved from structural spars made from composite as a weight-saving measure. Boeing has weight reduction as a key goal for the 787. Boeing is providing interim fixes which includes "aluminum stiffeners" alongside the spars for planes 1-6, which are currently being assembled in Boeing's Everett plant. Beginning with plane 7, a permanent fix, presumably thicker spars, will be incorporated. "That required the addition of hundreds more clips and fasteners", said Pat Shanahan, vice president and general manager of the 787 program [59].

On January 15, 2008, Boeing announced a further three month delay to the first flight of the 787 due to production issues. As of mid-January 2008, Boeing still said it plans to deliver the first 787 to launch customer All Nippon Airways in early 2009
Cause of 4th Delay:

- Boeing also attributes the latest delay in part to the slower-than-expected progress on work that suppliers. The plan was for initial assembly to be done be the supplier. The Final Assemble – consisting of a few large sections would then be done at Boeing Everette, WA facility. As Boeing would find out, the plan had not worked as it hoped and Boeing is now having to do a good part of the initial assembly of the 787 by itself, and plans to dump suppliers who are not performing to expectation [60].

7.7.1.1. Long-term impact of these operations Debacles to Airbus and Boeing's competitive positions

The fallout cost for both Boeing and Airbus is billion of dollars or Euros in delivery penalties and cost overruns. The reputation of both companies are also at stake. When Airbus first announced delays in the delivery of the A380, shares of parent company EADS plunged by over 30%.

Airbus is already implemented what it called Power8, a big restructuring plan that involves the loss of 10,000 jobs and the sale of several plants, which is meant to offset the losses caused by the delays in delivering the A380 [61, 62].

In 2005, Airbus estimated that it would need to sell only 270 of the planes to break even. In 2006, the break even point had jumped to 420 planes as a result of costly wiring problems which have now delayed delivery of the A380 by up to two years [63].

Boeing now faces having to make penalty payments to customers of the sort that have plunged Airbus, its European rival, into heavy losses [64, 65].

In conclusion, the sourcing of Engineering Design work is a strategic decision confronting an OEM [66]. Product design is a critical link in the product development supply chain. The decision must take into account the vertical integration question which is quite complex, requiring very careful consideration. For example, vertically integrating an activity while solving a specific problem may in fact create new ones for the OEM. The quantitative analysis methodology presented in this thesis work is only part of the tool to enable management make informed decision. The sourcing of Engineering Design decision should be made based on both qualitative and quantitative analysis.

8. Appendix – Model Equations

1. Additional–Staff-Required= max(0,Max-Staff-Capacity – Current-Staff-Level)

2. Average-Work-Quality=
   Max(Numb-of Design-Work-Completed)/Max(Design-Work-Perceived-to-be-Completed)

3. Cum-Design-Work-Don e= INTEG(Rate-of-Doing-Design-Work, 0)

4. Cum-Labor-Cost = INTEG(Rate-of-Labor-Cost-Increase, 0)
5.
Current-Staff-Level =
(Numb-of-Experienced-Staff + Numb-of-New-Hires + Over Time-Staff)*Design-Work-Finished-Switchoff)

6. Design-Rework-Discovery-Delay =
   Mean-Time-to-Discover-Rework*Effect-of-Work-Progress
+ (1-**Effect-of-Work-Progress**)*Mean-Time-to-Discover-Rework

7. Design-Rework-Discovery-Rate=
Undiscovered-Design-Rework/(Design-Rework-Discovery-Delay + Time-for-Issues-Resolution)

8. Design-Rework-Generation-Rate = Feasible-Work-Rate*(1-Quality)

Design-Work-Accomplishment-Rate = Feasible-Work-Rate*Quality

9. Design-Work-Finished-Switchoff =
if then else (Numb-of-Design-Work-Completed > Initial-Numb-of-Design-Work-to-Do ,0,1)

10. Design-Work-Perceived-to-be-Completed =
    Numb-of-Design-Work-Completed + Undiscovered-Design-Rework

11. Duration-of-Design-Work =
    if then else (Fraction-Really-Complete > 0.99,0, Design-Work-Finished-Switchoff)

12. Effect-of-Prior-Work-Quality-on-Quality =
Table-for-Effect-of-Prior-Work-Quality-on-Quality(Average-Work-Quality)

13. Effect-of-Work-Progress =
    Table-for-Effect-of-Work-Progress (Fraction-Really-Complete)

14. Feasible-Work-Rate = MIN(Potential-Work-Rate, Maximum-Work-Rate)

15. Fraction-Perceived-to-be-Complete =
    Design-Work-Perceived-to-be-Completed/Initial-Numb-of-Design-Work-to-Do

16. Fraction-Really-Complete =
Numb-of-Design-Work-Completed/Initial-Numb-of-Design-Work-to-Do

17. Hiring-Rate = Additional-Staff-Required/Hiring-Delay

18. Impact of New Hires & Over Time On Productivity =
    if then else(Current-Staff-Level > 0, (Numb-of-New-Hires*Relative-Productivity-of-New Hires + Over Time-Staff*(Productivity-of-Over Time-Staff/Ref-Productiv)+ Numb-of-Experienced-Staff)/Current-Staff-Level, 1)

19. Impact-of-New-Hires-&-Over Time –On-Quality =
if then else(Current-Staff-Level > 0, (Numb-of-New-Hires*Relative-Quality-of-New Hires + Over Time-Staff*(Quality-of-Over Time-Staff/Ref-Quality) + Numb-of-Experienced-Staff)/ Current Staff Level, 1)

20. Maximum-Work-Rate = Numb-of-Design-Work-to-Do/Minimum-Time-to-Complete-a-Design

21. Minimum-Time-to-Complete-a-Design = 20*Design-Complexity-Factor

22. Numb of Design Work Completed= INTEG (Design Work Accomplishment Rate, 0)

23. Numb of Design Work to Do=
INTEG (Design Rework Discovery Rate-Design Rework Generation Rate-Design Work Accomplishment Rate, Initial Numb of Design Work to Do)

24. Numb of Engineering Changes (EC) (%)"=
100*"Numb of Engineering Changes (EC)"/Initial Numb of Design Work to Do

25. Numb of Engineering Changes (EC) =
Cum Design Work Done-Numb of Design Work Completed

26. Numb of Experienced Staff= INTEG (Rate of New Hires Gaining Exp, Initial Numb of Exp Staff)

27. Numb of New Hires =
INTEG ((Hiring Rate-Rate of New Hires Gaining Exp)*Design Work Finished Switchoff, 0)

28. Potential Work Rate = Current Staff Level*Productivity

29. Productivity = Ref Productiv*Impact of New Hires & OverTime On Productivity

30. Productivity of Over Time Staff=
INTEG (-Productivity of Over Time Staff Decreasing*Duration of Design Work, Ref Productiv)

31. Productivity of Over Time Staff (%) = 100*Productivity of Over Time Staff/Ref Productiv

32. Productivity-of-Over Time Staff Decreasing=
Productivity of Over Time Staff/Over Time Productivity Decrease Rate

33. Quality=
Ref Quality*Effect of Prior Work Quality on Quality*"Impact of New Hires & Over Time On Quality

34. Quality of Over Time Staff= INTEG (-Quality of Over Time Staff Decreasing, Ref Quality)

35. Quality of Over Time Staff (%) =
100*Quality of Over Time Staff*Duration of Design Work/Ref Quality

36. Quality of Over Time Staff Decreasing=
Quality of Over Time Staff/Over Time Quality Decrease Rate

37. Rate of Doing Design Work=
Design Rework Generation Rate + Design Work Accomplishment Rate

38. Rate-of-Labor-Cost-Increase = Current-Staff-Level*Duration-of-Design-Work

39. Rate-of-New-Hires-Gaining-Exp = Numb-of-New-Hires/Time-for-New-Hires-To-Gain Exp

40. Table-for-Effect-of-Prior-Work-Quality-on-Quality([(0,0)-(1,1)],(0,0.05),(0.1,0.1),(0.2,0.2),(0.3,0.3),(0.4,0.4),(0.5,0.5),(0.6,0.6),(0.7,0.7),(0.8,0.8),(0.9,0.9),(1,1))

41. Table-for-Effect-of-Work-Progress([(0,0)-(1,1)],(0,1),(0.1,1),(0.2,1),(0.3,1),(0.4,1),(0.5,0.9),(0.6,0.75),(0.7,0.5),(0.8,0.25),(0.9,0.1),(1,0))

42. Total-Productivity = Current Staff-Level*Productivity

43. Undiscovered-Design-Rework =
INTEG (Design-Rework-Generation-Rate – Design-Rework-Discovery-Rate, 0)

44. Work-Change = Initial-Numb-of-Design-Work-to-Do – Numb-of-Design-Work-Completed

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